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THE
ACOUSTICS OF BUILDINGS

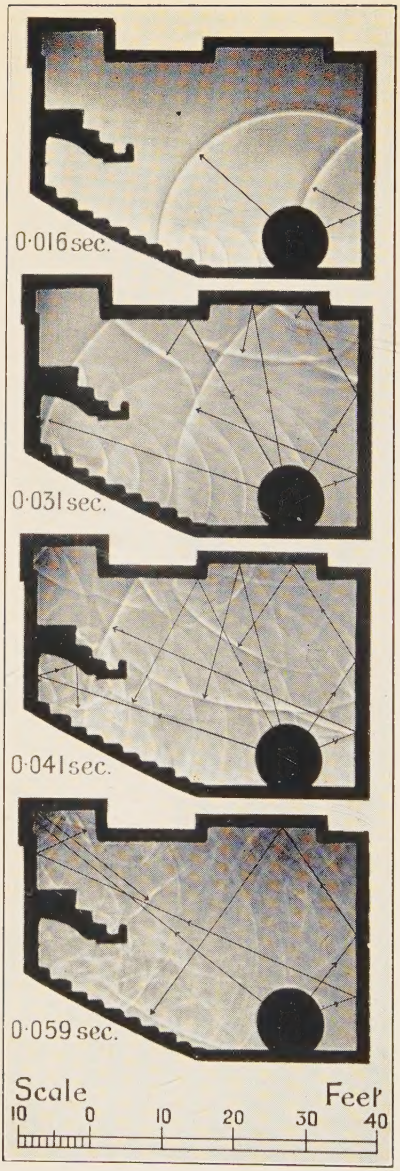

FIG. 56.—Sequence of sound-pulse photographs relating to the Royal Institution Lecture Theatre (Fleming). (See p. 131.)

THE ACOUSTICS OF BUILDINGS

BY

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PREFACE

THIS book owes its origin to the Tyndall Lectures delivered by one of us (G. W. C. K.) at the Royal Institution in 1926. The authors wish to record their obligations to Sir Wm. Bragg, at whose suggestion the book was undertaken. They are greatly indebted to their colleagues in the Physics Department at the National Physical Laboratory, in particular to Mr N. Fleming, for much valuable assistance: Mr T. S. Littler has also rendered effective help. The writers would also record their grateful thanks to Sir Joseph Petavel, Director of the National Physical Laboratory, for many kindnesses.

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THE ACOUSTICS OF BUILDINGS

CHAPTER I

THE PRODUCTION AND MEASUREMENT OF SOUND

General

BEFORE addressing ourselves to our subject, that is the behaviour of sound in buildings, it will perhaps be useful first to recall briefly the characteristics of sound and to outline the methods by which sound can be generated and measured, so far as they appertain to the acoustics of buildings.

Sound has its origin in vibrations, and is transmitted by the air as a form of wave-motion at a speed of about 1100 feet per second. It is also readily transmitted by solids and by liquids in which it travels normally at much greater speeds than in air; for example, sound may be conducted by solid rods or stretched wires to considerable distances and there made evident by the use of attached sounding-boards.

The sound-waves sent into the air by a vibrating body consist of alternations of condensation and rarefaction. The vibrating source, in moving forwards, compresses the air in front of it: this compression is rapidly relieved by being communicated to the next layer of air, and the state of compression thus travels outwards with the velocity of sound.

Meanwhile the source is recovering and moving backwards, thus sending out a region of rarefaction immediately behind the compression. This in turn is followed by another compression when the vibrating source begins to move forward again. The distance in the air by which the first condensation is in advance of the second condensation is called the wave-length of the sound concerned, and it is greater the slower the vibrations of the source. If the frequency of the source is n complete vibrations per second, then the wave-length is equal to one nth part of the distance travelled by sound in one second.

As in the case of light, sound-waves, on reaching the interface between two different media, are subject to reflection and refraction. In general, the laws are the same as those for light, but, since the wave-length of sound is usually large in comparison with the size of objects normally encountered, the reflected and refracted sounds spread considerably outside the limits to which light-waves would be confined. When the elasticity and density of the second medium or obstacle differ markedly from those of the first the sound is almost entirely reflected, and the amount refracted and so transmitted through the second medium is very small. We find on calculation * that if sound-waves in air were to fall on a truly rigid non-porous wooden or stone wall the sound energy which would penetrate the wall would amount to only a few parts in a million. Almost all rigid surfaces are more efficient as reflectors of aerial sound-waves than the best mirror is for light.

Sound may be focussed by curved reflectors or

* Rayleigh, *Theory of Sound*, 2nd edit., **2**, 88 (1896).

may be screened from a given region by interposed obstacles, provided the size of the reflector or of the obstacle is large compared with the wave-length of the sound. But, as previously remarked, owing to the long wave-lengths of most ordinary sounds—for example, the wave-lengths in speech range from a few inches up to, say, 20 feet—such focussing and screening effects are apt to be only of a partial character.

Owing to this fact that normal sounds usually spread outside the limits of optical laws, it is useful to have some analogous case which can be studied visually to give some idea of the manner in which sound-waves would behave. There is no simple analogy which is completely parallel, but the ripples on the surface of a liquid in an experimental ripple tank can usually be produced of a wave-length which, in relation to the size of any obstacles of convenient dimensions placed in the tank, corresponds satisfactorily with any acoustical condition it may be desired to imitate. Of course, this is only a two-dimensional effect which, strictly speaking, should be confined in its application to cylindrical sound-waves, but, as we shall see presently, it is frequently very helpful.

Sound is a form of energy, and once produced would continue for ever if it were not dissipated into heat or transformed into some other form of energy. When emitted by a point source far removed from all obstacles, sound spreads equally in air in every direction, *i.e.* the wave front is spherical. Owing to this spreading, the intensity at any point measured in energy units is inversely proportional to the square of the distance of the point from the source. Except

for the very loudest sounds, such as those from fog-horns, etc., it is usually accepted that sound suffers but little dissipation into heat in the air itself, so that for all ordinary sounds the inverse-square law holds good. In the case of sound generated within a room, the sound is absorbed at a rate depending on the porosity of the various surfaces in the room: the sound-waves penetrate the capillaries in the porous surfaces, where viscosity and allied effects rapidly convert the sound-energy into heat. If porous surfaces are absent, for instance as in a steel-lined enclosure or a hall with tiled or marble walls, sound echoes and re-echoes to and fro for a considerable time before it finally dies away.

Sound is further subject to the phenomena of interference. If two continuous sources of sound of the same amplitude and pitch—that is, the same frequency of alternations—are situated near each other, there will be regions in the vicinity where at any moment the condensation from one source will be exactly neutralised by a rarefaction due to the other. Half a vibration later the conditions will be reversed, but the waves will still neutralise each other. At such a point, in spite of the proximity of the sources, no sound will be audible at any time. At another point two condensations may arrive together and specially loud sounds will be heard. This distribution of regions of comparative silence and of enhanced loudness constitutes an interference field.

Interference will obviously be experienced when a source is near a reflecting wall, for the reflected waves proceed as from a virtual or image source, similar to the real source. In the case of plane-waves

impinging normally upon a perfectly reflecting wall, maximum loudness will be perceived at multiples of half a wave-length from the wall, while no sound will be noticeable at odd multiples of a quarter of a wave-length. The regions of maximum and of minimum sound are called nodes and antinodes respectively. If the wall is not a perfect reflector, the reflected train of waves will be less intense than the incident, so that the annihilation of sound at the antinodes will be only partial, while the loudness at the nodes will also be somewhat reduced. Indeed, as we shall presently see, a method of determining the reflecting power of a material is based upon measurements of the ratio of the intensities at such nodes and antinodes.

Suitable Sources of Sound

The sources of the sounds which may originate in a building are numerous and diverse, including as they may the whole range of musical instruments. It is intended here to refer only to those few sources that appear suitable for acoustical tests on buildings and building materials.

In general it is desirable in such tests to deal only with sources which are pure in the physical sense, that is those which emit a single fundamental note unaccompanied by harmonics or overtones. If the behaviour of a material to pure notes is studied over a wide range of pitch, then one can predict its behaviour towards a more complicated type of sound containing specified overtones. This use of pure tones has a sound mathematical basis. The wave form of vibration associated with a pure tone is that known as simple harmonic, and is represented

graphically by a curve of sines when displacement is plotted against time. Simple harmonic motion is the form associated with small oscillations of any freely vibrating body having only one degree of freedom. It can, moreover, be shown mathematically that the most complicated oscillation of any frictionless system may be made up of a series of vibrations of this kind, each of which might be excited separately if suitable precautions were taken. The mathematical reason for the pre-eminence of the simple harmonic type lies in the fact that it is the only type which retains its character absolutely unchanged when it is transmitted from one system to another.

In referring to the pitches of musical sources of sound, it may be noted that the notation used by Sabine and a number of writers on architectural acoustics does not coincide with the commonly accepted English notation, due originally to Helmholtz. Table I shows the two notations and the associated frequencies. Helmholtz's notation is generally adopted in this country. It may be added that the frequencies quoted in this book refer everywhere to double vibrations. Frequencies in France refer to single vibrations, and so the values are doubled.

Organ Pipes.

Among the simple musical sources which have been used in general acoustical work, the organ pipe has found extensive application. Sabine, for example, used it in much of his work. As regards purity, organ builders are familiar with the devices which produce the various qualities of tone. For

instance, the open pipe may contain the full harmonic series and the closed pipe only the odd members of the series. Overblowing, or using narrow pipes, favours the upper partials. The pipes of certain

TABLE I.—FREQUENCIES OF MUSICAL SCALE.

Notation.		Frequency for scientific purposes.
Helmholtz.	Sabine.	
C_1	..	32
C	C_1	64
c	C_2	128
* c^1	C_3	256
c^{11}	C_4	512
c^{111}	C_5	1024
c^{1v}	C_6	2048
c^v	C_7	4096

stops generate very brilliant notes which contain prominent harmonics. On the other hand, diapason or flute pipes give the nearest approach to a pure note, although harmonics are present to some extent. An analysis by Wegel and Moore † of the sound emitted by a diapason pipe of frequency 64 showed that traces of the octave and of the twelfth accompanied the fundamental, the energy associated with these harmonics being only about 10 per cent. of that of the fundamental. Sounds from the tin whistle ‡ and from the ocarina also appear to be remarkably pure.

In suitable circumstances it is possible to filter out undesired harmonics. An acoustical method,

* Middle *c* of piano.

† Wegel and Moore, *Amer. Inst. Elect. Engrs. Trans.*, **43**, 457, 1924.

‡ Fournier d'Albe, *Nature*, **114**, 537, 1924.

due to Quincke,* is illustrated in Fig. 1. The sound is led through a short conduit which carries a branch tube fitted with a sliding piston. When the tube is tuned by means of the piston to any desired frequency, it will absorb sounds of that frequency

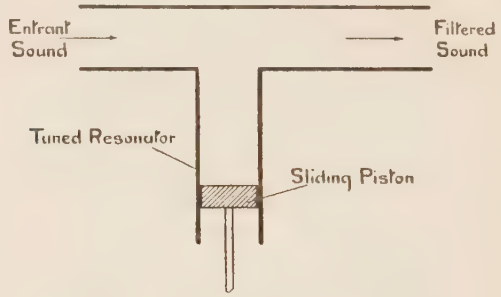

FIG. 1.—Quincke's acoustical filter.

passing through the conduit, but will allow the remaining sounds to pass on. A later illustration (Fig. 45) shows how Taylor purified the note from an organ pipe by using a series of such filters tuned to the several harmonics of the fundamental.

In recent years Stewart † has devoted much attention to the design of acoustical filters of various types, but, so far as we are aware, they have not yet been used in large-scale practical acoustics.

An important characteristic of the organ pipe is that the wave-length of its fundamental sound is a definite function of its size. When the temperature of the air increases, the velocity of sound is increased; in consequence, the note emitted by the pipe is sharpened, but its wave-length remains the same. The interference pattern in a room depends upon

* Quincke, see Rayleigh's *Theory of Sound*, 2nd edit., **2**, 210, 1896.

† Stewart, *Phys. Rev.*, 1922 *et seq.*

the wave-length, so that when an organ pipe is used as a source, the pattern will not alter as the temperature of the room changes. When interference systems are under study this may well be an advantage.

The emission from an organ pipe is somewhat restricted in volume ; under very soft blowing the pipe will not speak, and when overblown the harmonics predominate. To augment the intensity one may increase the number of pipes, but the gain in intensity is not necessarily proportional, as the several pipes may react on each other.

Sirens.

Sirens were much used in early acoustical work. In all types a blast of air issuing from a nozzle is obstructed by a rotating perforated disc. The perforations which are equally spaced around the disc come in turn before the nozzle, and puffs of air pass through the holes. If the disc is rotated sufficiently rapidly, the periodic recurrence of the puffs results in the emission of a musical note of calculable frequency.

In some of the earlier forms of siren the holes were drilled obliquely to the surface of the disc, so that the blast of air was also responsible for rotating the disc. It was thus impossible to dissociate intensity from frequency. In present-day models the siren is motor-driven. Within limits the sound amplitudes are proportional to the pressure of the air supply. It does not appear that the note from a siren has been directly analysed experimentally, but it is known, however, that the note is not pure. With a circular nozzle and circular holes each of a sectional

area equal to that of the nozzle, purity is most nearly approached when the distance between centres is about twice the diameter of a hole. Milne and Fowler * have calculated that the intensities of the octave and twelfth emitted by such a siren should each be of the order of $\frac{1}{20}$ of the fundamental, while the third harmonic should be even less pronounced. An indirect experimental test gave results in connection with the octave which agreed fairly well with calculation.

The same authors describe a special form of siren for giving pure tones. In this the nozzle is rectangular in section, and the holes in the rotating disc are specially shaped so that the uncovered area of the nozzle varies in approximately a simple harmonic manner. Fig. 2, Plate I, shows the plate of such a siren in use at the National Physical Laboratory. Milne and Fowler tested their siren by the use of a hot-wire microphone (p. 18) tuned to a definite frequency. It was found that as the speed of the siren was varied little response of the microphone occurred except when the siren was rotating at such a speed that the frequency of passage of the holes was equal to the resonant frequency of the microphone. At lower speeds, the microphone did not indicate appreciable harmonics of the fundamental note, the conclusion being that the sound was reasonably pure when the siren was emitting notes of low frequencies. It would be interesting to analyse the emitted sound at high speeds, for the sound does not then seem to have that flute-like quality usually associated with pure tones.

* Milne and Fowler, *Roy. Soc. Proc.*, **98**, 414, 1921.

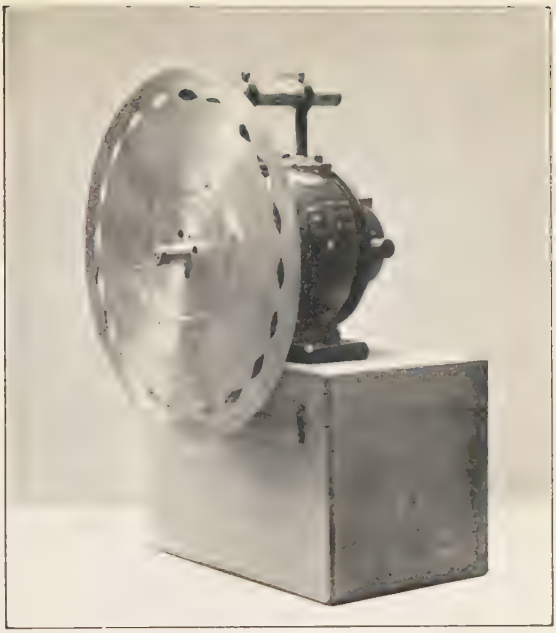

Fig. 2.—Pure-tone siren (motor driven). See p. 10.

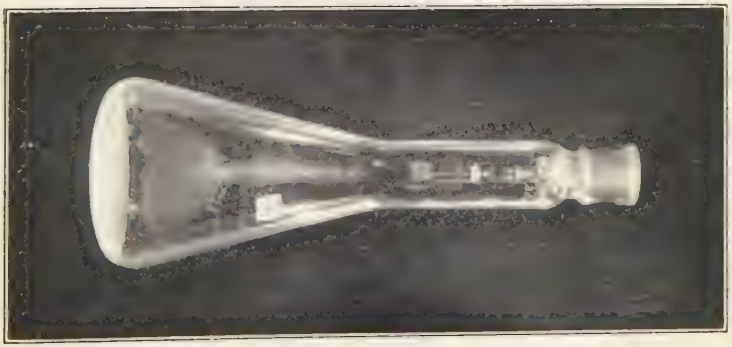

Fig. 3.—Cathode-ray oscillograph. See p. 11.

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Electrical Loud-Speakers.

A very convenient source of sound is an electrical loud-speaker, actuated by alternating current of pure sine-wave form. Such currents can be obtained by the use of thermionic valve oscillators: these are fairly easily constructed, or they are now purchasable. Normally the wave-form is not absolutely pure, but harmonics may be suppressed either by suitable electric filters, or alternatively by amplifying the output by means of a valve amplifier of which the anode circuit is tuned to the fundamental required. The wave-form of the alternating current can be conveniently tested by means of a cathode-ray or other type of oscillograph suitable for acoustic frequencies (Fig. 3, Plate I).

The frequency of the note can be readily altered by adjustments of the electrical circuits of the oscillator; and a loud-speaker thus forms a very "elastic" generator of sound offering the dual advantages of a wide range of pitch and intensity from a single instrument.

There are two main types of loud-speaker—the so-called electromagnetic and electrodynamic. For some purposes the ordinary electromagnetic type of loud-speaker, in which an iron diaphragm oscillates under the influence of the varying strength of an electromagnet (*cf.* Fig. 12), may be used. It is, however, not quite constant enough for precision measurements; in particular, its sensitivity usually varies appreciably with the temperature, possibly because the gap between the magnet and the diaphragm alters.

An electrodynamic type of loud-speaker is pre-

ferable for measurement purposes. This instrument, in which a non-magnetic diaphragm carries a coil of wire moving in a constant magnetic field (*cf.* Fig. 13), has been found by Davis and Fleming * at the National Physical Laboratory to be satisfactorily constant and free from lag, and over a range of activity of about 15,000 fold to have an acoustical energy emission directly proportional to the square of the exciting current. The diaphragm may advantageously be corrugated to help to confine its vibrations to the fundamental mode.

It should, of course, be realised that the construction of an electromagnetic or electrodynamic loud-speaker used for sound generation is essentially the same as that of the corresponding microphone used for sound measurement (see p. 20). When the instrument is used as a loud-speaker an alternating e.m.f. is applied to the coils, producing in consequence vibration of the diaphragm and emission of sound. Alternatively, when the instrument is employed as a microphone the incidence of sound-waves on the diaphragm sets up an alternating e.m.f. at the terminals of the coils.

Similarly, most of the instruments about to be described in connection with the measurement of sound could also be used in a reverse manner to act as sources of sound. For example, the selective instruments of Webster (p. 17), or Tucker and Paris (p. 18), could be adapted for such purposes, and should give very pure notes of the frequency to which they are tuned. The condenser microphone mentioned later (p. 21) would also form a source which would reproduce accurately in acoustic wave-

* Davis and Fleming, *Phil. Mag.*, **2**, 51, 1926.

form the wave-form of the electrical input used to excite it. At present, however, such instruments have not been put into general use.

In Fig. 19, which illustrates a combined electrical equipment (*i.e.* a loud-speaker source and apparatus for measuring the emitted sound), a valve-oscillator unit is indicated diagrammatically in the top right-hand corner, employing the usual electrical symbols for valves, batteries, inductances, and capacities.*

With reference to loud-speakers, it should be remembered that an ordinary horn type exhibits resonances; in other words, the volume of sound emitted is particularly great for certain frequencies. If, however, we are dealing only with pure tones of a single frequency, resonance effects will not seriously detract from the value of the instrument.

Measurement of Sound Intensity

While the ear is the ultimate criterion in acoustical questions, it cannot be relied upon in quantitative measurements of intensity, and we have accordingly to adopt other means. It is difficult, however, to find an instrument which can compete with the ear as regards sensitiveness and the remarkable ranges of frequency and intensity to which it will respond.

In the measurement of the intensity of sound various methods have been adopted, from which it is possible to deduce the amplitude of vibration of the air particles in the sound-wave, or of the degree of variation of the air density or pressure associated with the alternations of compression and rarefaction.

* Useful details of the design of valve oscillators will be found in Glazebrook's *Dictionary of Applied Physics* (Macmillan), **2**, 899.

For ordinary sound of a given frequency in air the maximum amplitude of vibration, the maximum oscillatory velocity, and the maximum oscillatory pressure or density are all proportional to one another. The intensity of a sound at a point is usually expressed in energy units, either in terms of the rate of flow of sound energy across unit area, or in terms of the energy contained in unit volume at the point in question. In either case the intensity in energy units is proportional to the square either of the amplitude or of the oscillatory velocity, or of the oscillatory pressure.

Lord Rayleigh made an estimate in 1877 of the amplitude of vibration for a minimum audible sound. He employed a whistle as a source and measured the mechanical energy used in blowing it. He found the sound was just audible at 820 metres from the whistle, and he calculated the energy passing through each square centimetre of a hemisphere of this radius. From this it is possible to deduce an upper limit for the amplitude of aerial vibration, and Rayleigh * found it to be in this case about 8×10^{-8} cm. The actual amplitude must, however, have been much less than this, for it was assumed that all the energy of blowing the whistle was converted into sound. Rayleigh also obtained comparable results using a tuning-fork and resonator as source; in this experiment he calculated the rate of emission of energy from the rate at which the vibration of the tuning-fork died away.

A number of highly ingenious methods have been

* Rayleigh, *Roy. Soc. Proc.*, **26,** 248, 1877. See also *Theory of Sound*, 2nd edit., **2,** 434, 1896.

used for measuring the absolute intensity of sound, but they are not at present readily applicable to the practical testing of building materials. Töpler and Boltzmann * used the phenomenon of optical interference to make refractometric measurements of the density variation at the nodes of stationary waves in air. Rayleigh has given the theory of another method which depends on the measurement of the radiation pressure exerted by a sound-wave, that is, the pressure by which an incident sound-wave tends to push a reflecting wall away from the source. An inquiry into the whole question is now in progress at the National Physical Laboratory.

Rayleigh Disc and Double Resonator.

An apparatus which has frequently been used in sound intensity measurements is the well-known Rayleigh disc † in conjunction with a double resonator, which latter was suggested by Boys ‡ to increase the sensitiveness. The theory of such resonators has been given by Rayleigh. § The resonator consists in practice of two tunable cylindrical vessels which are connected together by a short neck (Fig. 4). When the instrument is exposed to the influence of a note having the pitch to which it is tuned, pronounced oscillatory excursions of the air in the neck are set up. The velocity of this air current is measured by means of a thin circular disc suspended in the neck and inclined at an angle of 45° to the axis. This disc tends to set itself at

* Töpler and Boltzmann, *Pogg. Ann.*, **141,** 321, 1870.

† Rayleigh, *Phil. Mag.*, **14,** 186, 1882. See also *Theory of Sound*, 2nd edit., **2,** 45, 1896.

‡ Boys, *Nature*, **42,** 604, 1890.

§ Rayleigh, *Phil. Mag.*, **3,** 338, 1902.

right angles to the air current, the turning moment being proportional to the square of the average air velocity. A fine quartz fibre is used to suspend the disc, and the turning moment may be calculated either from the deflection of the disc under the influence of the sound, or from the rotation of the suspended head necessary to reduce the deflection to zero. Glass windows are provided in the neck

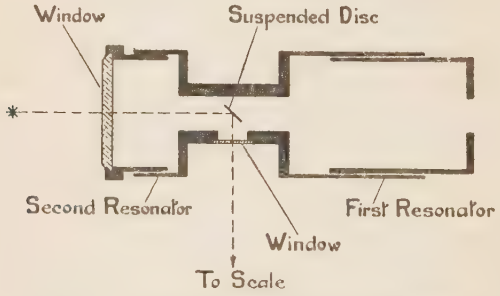

FIG. 4.—Rayleigh disc and double resonator.

and in the end of the resonator, and the deflection is observed by the movement of a beam of light reflected from the disc on to a scale. For small movements the angular deflection θ of the disc is proportional to the intensity I of the sound measured in energy units. More accurately, in comparing the intensities I_1, I_2 of two sources of the same frequency from their corresponding deflections θ_1, θ_2 as read upon the instrument, use should be made of the equation

$$\frac{I_1}{I_2} = \frac{\theta_1}{\theta_2} \cdot \frac{\sin 2(\phi - \theta_2)}{\sin 2(\phi - \theta_1)}$$

where ϕ is the initial angle between the axis of the tube and the normal to the disc.

The advantage of the instrument is its extreme

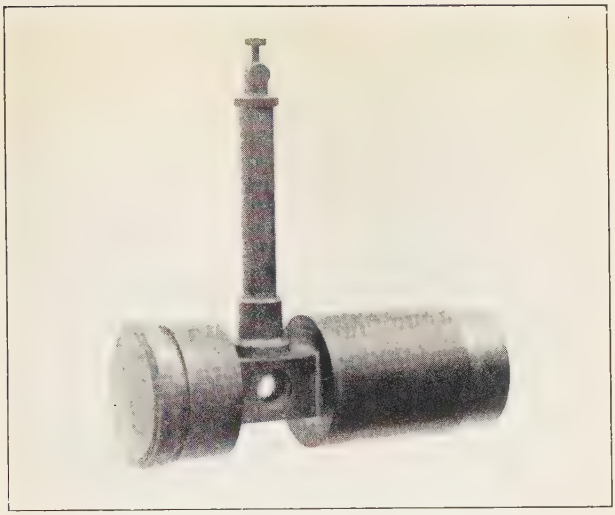

FIG. 5.—Photograph of Rayleigh disc and double-resonator apparatus. See p. 17.

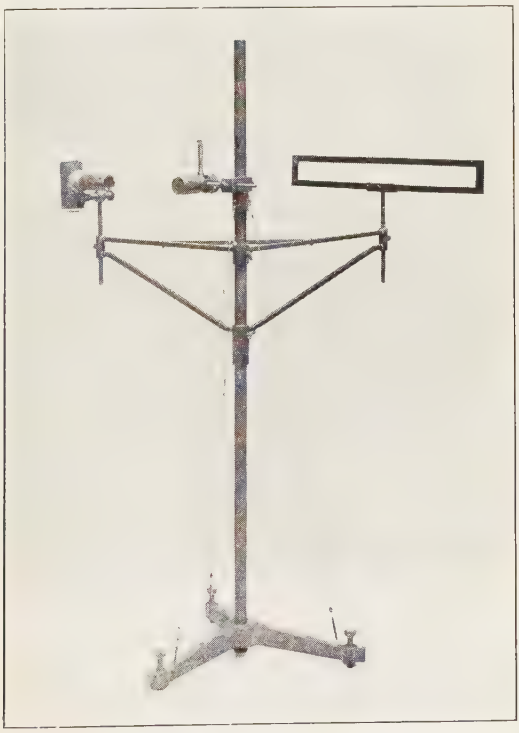

FIG. 6.—Photograph of Rayleigh disc apparatus complete with lamp and scale, as used at the N.P.L. See p. 17.

[*To face page* 16.

sensitiveness to a sound of the correct pitch. Indeed, it will measure sounds so feeble as to be barely perceptible by the ear. The selectiveness of the device, that is, its insensitiveness to other frequencies, is particularly useful when it is desired to avoid the effects of any components of a sound other than the chosen pitch. The disadvantage of the apparatus is that for the same pitch several instruments of different sensitiveness are needed if a wide intensity range has to be covered; and a large number of resonators are necessary to cover the frequency range which obtains in speech and music. Figs. 5 and 6, Plate II, show respectively a Rayleigh disc resonator, and the complete instrument with stand, lamp, and scale as used at the National Physical Laboratory.

Webster Phonometer.

Webster * has evolved a compact portable phonometer which, as shown in Fig. 7, consists essentially of a large tunable resonator in the mouth of which a diaphragm is held by means of three coplanar stretched wires symmetrically disposed. Under the influence of sound of the correct pitch the resonant excursions of air at the mouth set the diaphragm in oscillation, the magnitude of the oscillation being greatest when the supporting wires are also correctly tuned. The motion of the diaphragm is observed through the medium of a steel point attached to the back of the diaphragm, which bears against a very small mirror on a torsion strip in such a way that the mirror is rotated when the diaphragm moves.

Light from a small lamp lighted by a dry battery

* Webster, *Engineering*, **111**, 763, 1921.

passes through the glass back of the resonator and is observed by means of an eyepiece. From the swinging excursions of the image of the lamp, as observed on the scale of the eyepiece, the amplitude of vibration of the diaphragm may be calculated. The instrument can be tuned over two octaves, and when properly tuned will compete in sensitiveness with the human ear, though only over

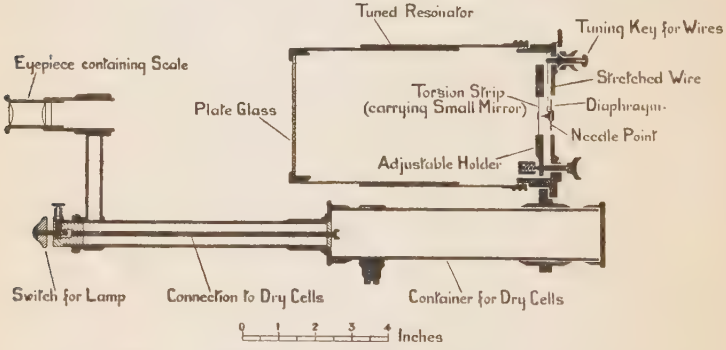

FIG. 7.—Webster's portable selective phonometer.

a limited range of frequency. Webster states that, by reading to 0·1 mm. on the graticule of the eyepiece, disc displacements of 1/24000 mm. can be detected. Fig. 8, Plate III, is a photograph of the Webster phonometer with the back removed.

Tucker Hot-Wire Microphone.

In the hot-wire microphone of Tucker and Paris * an exceedingly fine platinum wire 0·0006 cm. in diameter is placed in the form of a grid in the neck of a simple tunable resonator (Fig. 9). A heating current passes through the wire and heats it to just below red heat. The cooling effect of the air currents in the neck arising from resonance depends upon the

* Tucker and Paris, *Phil. Trans. A.*, **221**, 389, 1921.

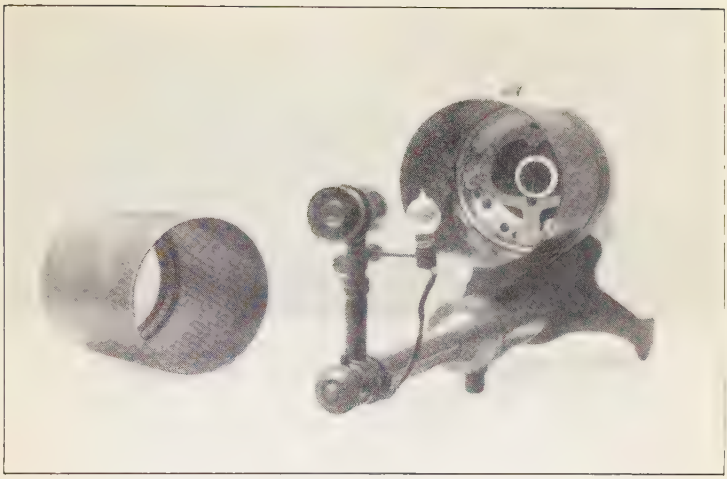

FIG. 8.—Photograph of Webster's phonometer with back removed. See p. 18.

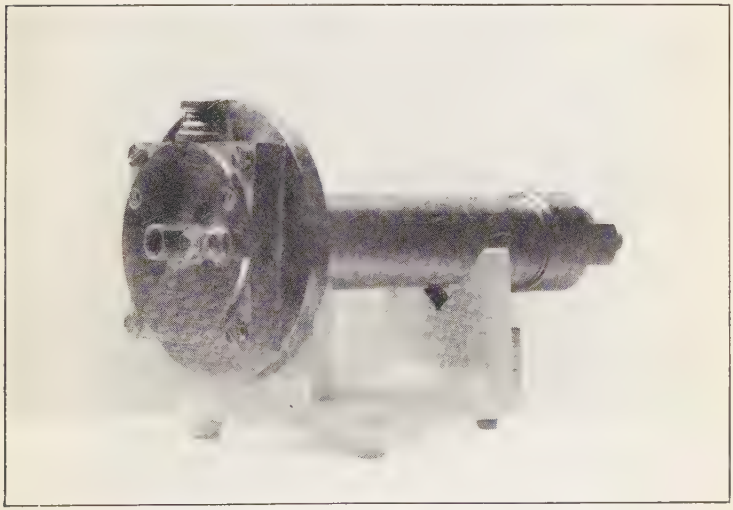

FIG. 10.—Photograph of Tucker selective hot-wire microphone. See p. 19.

[*To face page* 18.

intensity of the incident sounds. Cooling of the wire results in a decrease of its electrical resistance, and this decrease is measured by a Wheatstone's bridge arrangement. The calibration of the instrument is effected by observation of the cooling effect of steady air streams of known velocity. The calibration curve is somewhat complicated, but within certain limits the steady change of resistance is proportional to the intensity of the incident sound

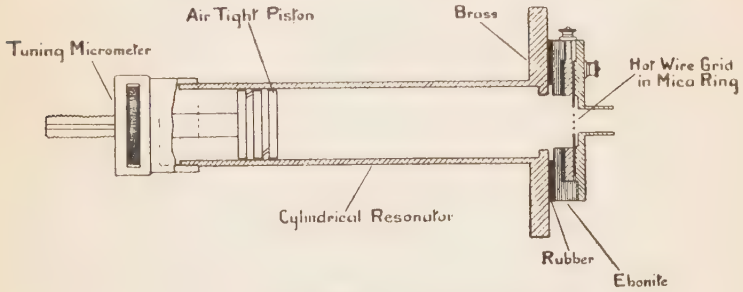

FIG. 9.—Tucker selective hot-wire microphone.

measured in energy units. Each resonator is tunable over a limited range by adjusting the piston, but, in common with other selective instruments, a series of resonators varying considerably in size is necessary if a wide range of frequencies has to be covered. Fig. 10, Plate III, is a photograph of an instrument designed for frequencies of about 500 vibrations per second. Fig. 11 shows in the case of an instrument tuned to 240 vibrations per second the degree of response to pure notes of adjacent frequencies.

While the hot-wire device is very sensitive for low frequencies (such as 100 vibrations per second), it becomes less so as the frequency rises. The practical upper limit is about 500 to 1000.

It may be added that the hot-wire microphone proved of great assistance during the war in detecting the positions of heavy guns.

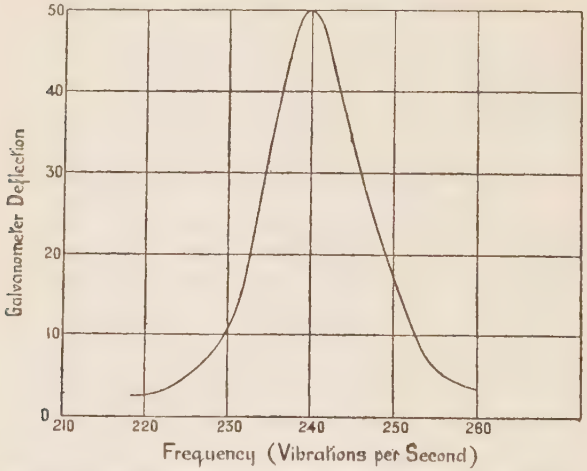

FIG. 11.—Curve showing selectiveness of response of hot-wire microphone tuned to frequency 240.

Telephonic Microphones.

A valuable instrument for sound measurement is an electrical microphone combined with some device for measuring the alternating current generated. As already indicated (p. 11), there are several types of microphone. Carbon-granule microphones (as used in the transmitter of an ordinary telephone) are somewhat inconstant, and an ordinary electromagnetic telephone receiver forms a more satisfactory instrument for measurement purposes. In this a thin iron diaphragm is clamped over, but not quite touching the poles of a magnet. On acoustic excitation, the diaphragm in moving to and fro generates an alternating electromotive force in the windings around the magnet. In experimental work,

the usual ebonite cap which clamps the diaphragm is preferably replaced by a metal clamp, such as that illustrated in Fig. 12. As previously remarked, the sensitivity of the instrument varies somewhat with temperature, presumably because differential expansion of the diaphragm relative to the clamp causes distortion, and so affects its equilibrium distance from the poles of the magnet. The movement of an electromagnetic loud-speaker (p. 11)

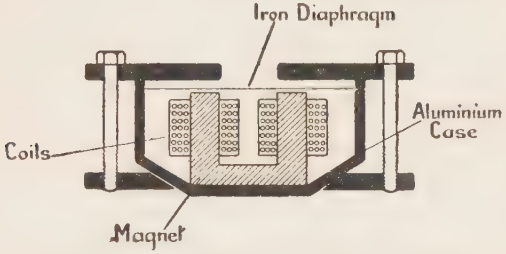

FIG. 12.—Modified electromagnetic microphone.

may also be used as a microphone: it is more sensitive than a telephone receiver, but has the same tendency to inconstancy. As already observed (p. 11), the electrodynamic type of loud-speaker movement (Fig. 13) is found to be preferable for purposes of measurement. Fig. 14, Plate IV, is a photograph of the several types of microphone.

Generally speaking, commercial types of microphones exhibit resonance within the range of acoustic frequencies. The methods of avoiding such resonance effects are to subject the diaphragm to either very high or very low tension, so as to bring the resonant frequency well above or well below the speech or music range.

Among the microphones with a high-tension diaphragm is the electrostatic or condenser micro-

phone described in 1917 by Wente.* This was specially designed for acoustical measurements, and has since been used extensively in researches by the staff of the Western Electric Company in New York. A recent form of the instrument † is illustrated in Fig. 15, and Fig. 16, Plate IV. It consists

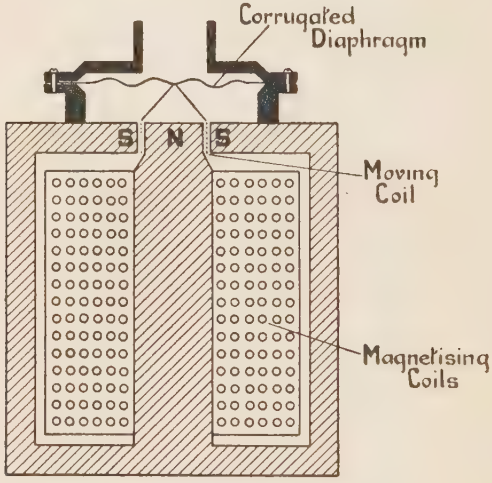

FIG. 13.—Electrodynamic microphone.

essentially of a tightly stretched thin steel diaphragm separated from a brass back plate by about 1/1000-inch air gap. The plate and the diaphragm form the two plates of an electrical condenser, which is charged by being permanently connected to a battery of about 200 volts through a high resistance. When the diaphragm vibrates under the action of sound, the capacity of the condenser varies, and an alternating electromotive force is set up. Annular grooves are cut into the face of the back plate, to

* Wente, *Phys. Rev.*, **10,** 39, 1917.

† Crandall, *ibid.*, **11,** 449, 1918; Wente, *ibid.*, **19,** 498, 1922.

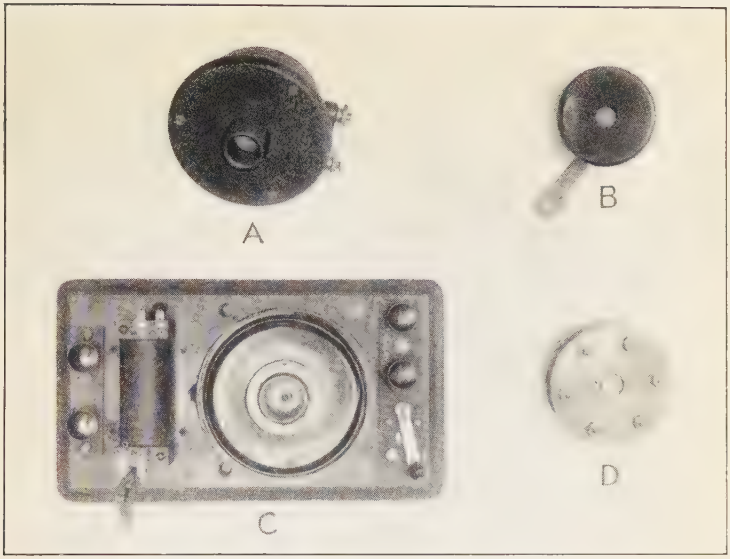

FIG. 14.

A. Electromagnetic microphone (loud speaker movement).
B. Electromagnetic microphone (small telephone movement).
C. Electrodynamic microphone (loud speaker unit).
D. As B, but ebonite cap replaced by metal clamp. See p. 21.

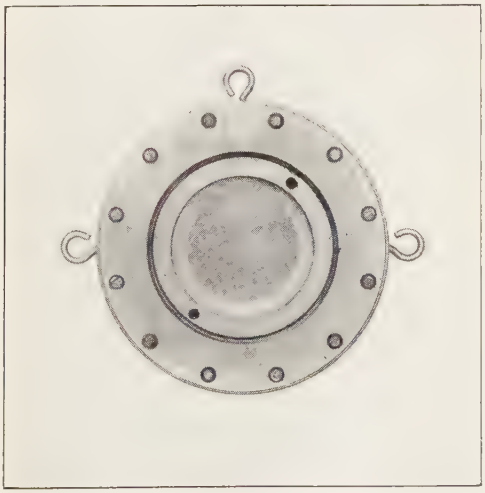

FIG. 16.—Photograph of Wente's electrostatic microphone. See p. 22.

[*To face page* 22.

give the diaphragm the requisite damping. To keep out moisture the space surrounding the back plate is sealed off by means of a thin rubber sheet, which has the advantage of maintaining the pressure within the air gap of the instrument substantially atmospheric. Owing to the tight stretching of the steel diaphragm, its natural frequency of vibration is very high—some 10,000 to 20,000 vibrations per

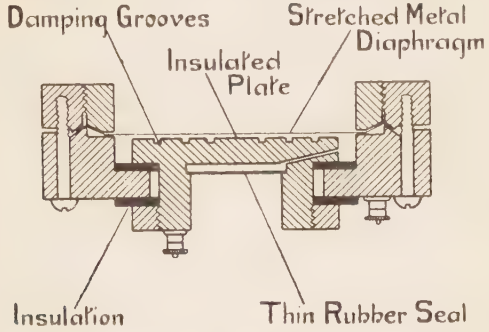

FIG. 15.—Illustrating Wente's electrostatic or condenser microphone.

second, and so the microphone is almost uniformly sensitive to sounds over a wide range of acoustical frequencies. Fig. 17 shows the relation for a particular case between the frequency and the electrical output of an instrument (expressed in millivolts for acoustic pressures measured in dynes per sq. cm.).

While there is considerable loss in sensitiveness due to the high tension of the diaphragm, the advantage of uniform response is very great for certain purposes. Furthermore, in changing from sound of one frequency to another substantially different, it is not necessary to employ a second instrument, as is the case with most of the devices used in conjunction with acoustical resonators.

The electrostatic microphone may also be used for recording the wave-form of a sound and for wave analysis. If selectivity is desired, it is readily possible to introduce an electrical tuning device into the circuits. The microphone with its tuned circuit

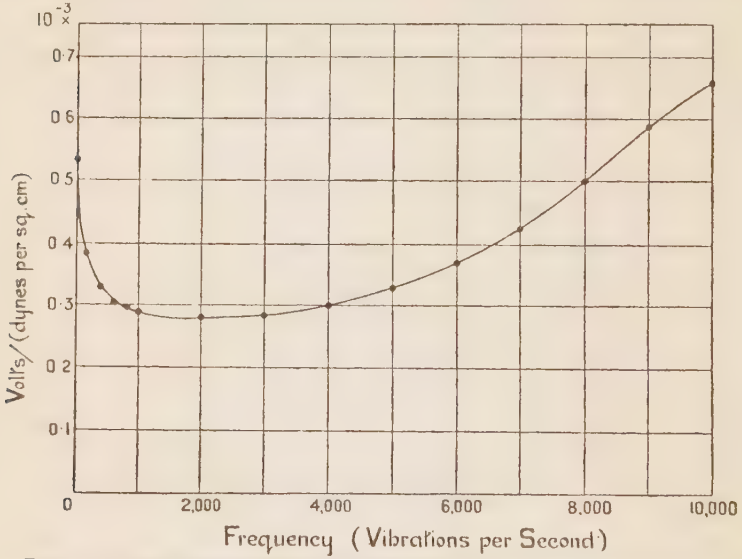

FIG. 17.—Curve showing response of Wente's electrostatic microphone to notes of various frequencies.

may then be used as a selective instrument over an exceedingly wide range of resonant frequencies with no more trouble than turning the knobs of a tuning condenser.

A Combined Equipment for Generating Sound and Measuring Telephonic Currents

The alternating electromotive forces set up in the several types of electrical microphones are small, and special devices are necessary to measure them. For this purpose the e.m.f.'s are magnified by dis-

tortionless valve amplifiers, and the amplified alternating current is then measured by a hot-wire milliammeter of a type suitable for small high-frequency currents. The amplifier may be calibrated by means of small alternating e.m.f.'s derived from the secondary of a variable mutual inductometer through the primary of which is passed an alternating current of the same frequency as that of the microphone current.

To avoid any vagaries due to valve amplification it is well in practice to calibrate each microphone reading as it is taken. For this purpose a selector switch is arranged, so that the unknown e.m.f. from the microphone or the known variable e.m.f. from the calibrated inductometer may be connected alternately to the input of the amplifier system. The inductometer is then adjusted until the two milliammeter deflections are equal.

This procedure is specially convenient when the source of sound used is an electrical loud-speaker. Fig. 18 illustrates diagrammatically the circuits in such a case, and Fig. 19 shows the complete equipment.* The loud-speaker is actuated by a valve-oscillator unit which, if properly designed, will give an electrical output of exceptionally pure wave-form, the frequency being readily controllable by the electrical constants of the resonant circuits. Residual imperfections are reduced by the tuned amplifier Q, which acts as a filter. The alternating current actuating the loud-speaker is derived from the valve-oscillator output by an air-core transformer or other suitable means and passes through the controlling resistance R and an ammeter A_1.

* Davis and Fleming, *Phil. Mag.*, **2**, 51, 1926.

The microphone (which may, for example, be used in exploring an acoustic field or in testing the transmission of sound through materials) is connected through the selector switch K to the input of the tuned amplifier system, shown for convenience in Fig. 19 as two separated units U and V. The output

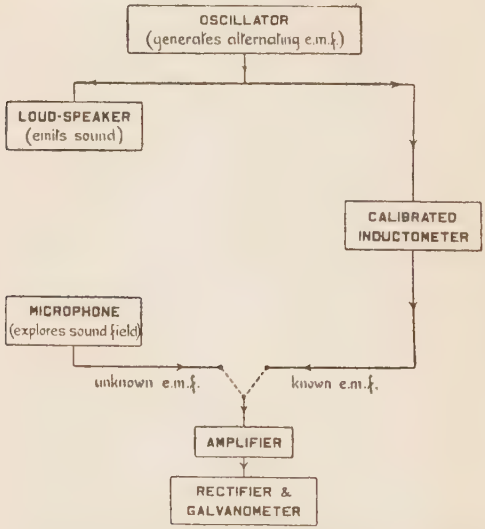

FIG. 18.—Diagrammatic representation of combined loud-speaker and electrical microphone equipment for the production and measurement of sound.

of the amplifier is conveniently recorded by a hot-wire milliammeter or vacuum thermojunction and galvanometer. The comparison e.m.f. from the calibrated inductometer is derived by suitably coupling the primary of the inductometer to the loud-speaker circuit so that a current (measured by the milliammeter A_2) is sent through the primary which is identical in frequency with that actuating the loud-speaker. The secondary of the variable inductometer is then connected to the selector switch K.

The complete equipment allows a wide range of frequency and intensity to be dealt with without any changes except those involved in tuning the electrical circuits. In practice the electromotive forces involved are so small that interference from electric-light wiring, etc., may be pronounced, and certain of the leads must therefore be adequately

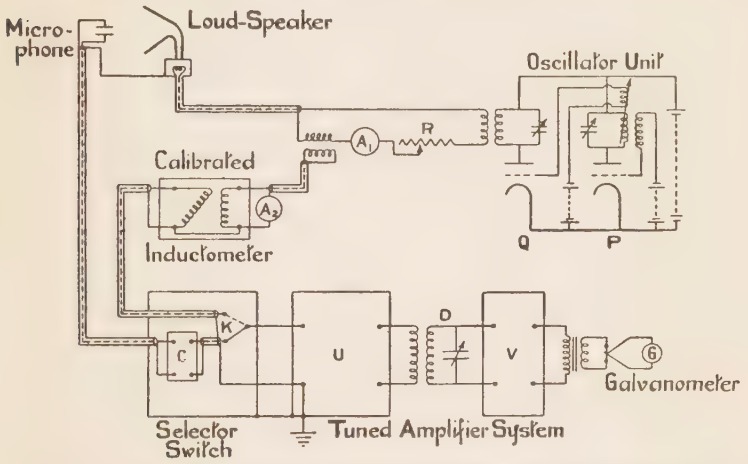

Fig. 19.—Electrical circuits of combined loud-speaker and microphone equipment for the production and measurement of sound.

screened by earthed metal tubing. The oscillator unit should be situated as far as possible from the rest of the apparatus; and the amplifier system, selector switch, etc., should be completely screened in metal boxes. The leads to the loud-speaker should also be shielded and, together with the case of the loud-speaker, suitably earthed. In conditions where serious interference arises from outside sources, the amplifier system itself may be tuned as indicated at *D* in Fig. 19, or fitted with suitable electrical filters to suppress disturbing effects: such procedure, however, limits the general utility of the

amplifier. If a condenser microphone is employed then, owing to its high electrical impedance and the extreme smallness of the generated e.m.f.'s, greater amplification is required and the apparatus becomes specially liable to interference from outside sources. Indeed, experience suggests that when uniform sensitivity of the microphone is not essential it is better to use other and more sensitive types.

The amplifiers are coupled by what is known as the resistance-capacity method, and, when properly constructed, introduce no distortion. Further, the valves and other components throughout the equipment should all be of sufficient power and carrying capacity to deal with the currents involved without introducing distortion.

The equipment is not quite so advantageous in the case of notes of low acoustic frequency, as the oscillator coils then necessary are somewhat large and costly; furthermore, ordinary loud-speakers are usually rather insensitive in the low-frequency region.

An incidental advantage of the equipment is the ease of testing the purity of the wave-form of the current through the loud-speaker. For this purpose the loud-speaker circuit may be connected to some form of oscillograph, a cathode-ray oscillograph being especially convenient.

If a simple telephone receiver is connected in place of the hot-wire milliammeter to the output terminals of the amplifier, one can readily detect by ear whether the alternating e.m.f.'s from the microphone and from the inductometer are pure or of similar wave-form. Alternatively, it is possible to connect a cathode-ray oscillograph to the output terminals of the amplifier and so study the actual

wave-form, but for this purpose greater amplification is necessary. Additional valves must then be used, and the several components of such multi-valve amplifiers will require careful and separate screening to avoid reaction and howling effects.

The Analysis of Sounds

It is sometimes desirable to ascertain whether the note from a given source is pure or whether the fundamental is accompanied by harmonics. This is most readily achieved by studying the wave-form of the sound, for which purpose various methods have been used. Some experimenters have devised means of recording the vibrations of a diaphragm under the action of sound: the needle trace upon a gramophone record is, in fact, such a record adapted for reproduction purposes. In the Miller phonodeik * and the Low-Hilger audiometer † optical devices are employed for recording the nature of diaphragm movements upon moving photographic paper. These methods are usually somewhat defective owing to resonances of the diaphragm and other parts of the apparatus, so that sounds of certain frequencies have unduly great effects upon the instrument. The resulting records of the wave-forms are therefore distorted when resonant frequencies occur among the components of the test sound.

As already stated (p. 22), a type of apparatus which is almost wholly free from resonance effects over the speech and music range is the condenser microphone. For the purposes of wave-recording,

* Miller, *B.A. Report*, Winnipeg, p. 414, 1909.
† *Engineering*, **117**, 108, 1924.

the minute alternating e.m.f.'s generated are magnified by the aid of a valve amplifier, and the amplified electrical wave-form is observed by means of a suitable oscillograph and, if desired, analysed subsequently (p. 11). Alternatively, a tuned amplifier may be used and measurement made of the current output from the amplifier when it is tuned in turn to various frequencies.* With the first method a pure sine-wave form will be obtained when a pure sound is employed: with the second method the analysis is performed by the instrument, and for pure tones the output from the amplifiers will be practically nil for all frequencies except the fundamental concerned.

The Sensitivity and Range of the Ear

In interpreting acoustical data for buildings it is necessary to realise the range and limitations of human audition as regards both intensity and frequency.

As regards the range of intensity, aerial vibrations may be too minute to give rise to audible sounds, or they may be so powerful that sensations of "feeling" are excited and irritation or actual pain may be experienced.

Table II expresses for various frequencies the upper and lower limits of intensity detectable by the ear in terms of (*a*) the R.M.S. oscillatory air-pressure, and (*b*) the corresponding calculated amplitude of the air particles. It will be seen that the ear is especially sensitive in the frequency region

* Wegel and Moore, *Amer. Inst. Elect. Engs. Trans.*, **43**, 457, 1924.

1000–5000 vibrations per second. It is interesting to note that this is the region which carries those characteristics of speech found to be essential to intelligibility (see p. 35).

TABLE II.—INTENSITY RANGE OF THE EAR *

Frequency.	R.M.S. Oscillatory Pressure		Amplitude	
	for minimum intensity.	for maximum intensity.	for minimum intensity.	for maximum intensity.
Vibrations per sec.	Dynes per sq. cm.	Dynes per sq. cm.	cm. $\times 10^{-8}$.	cm. $\times 10^{-2}$.
32	1·0	..	17,000	..
64	0·15	300	1,200	2·5
128	0·03	900	120	4
256	0·006	3000	12	6
512	0·002	6000	2	6
1,024	0·0009	4000	0·5	2
2,048	0·0006	1500	0·2	0·4
4,096	0·0007	..	0·1	..
8,192	0·0015	..	0·1	..
16,384	0·1	..	3·2	..

It will be noted that the range of intensity (in energy units) covered by the human ear in the middle of its frequency range is amazingly large—of the order of a million-million-fold. It is equally noteworthy that the ear can pick up a pressure variation as small as one-thousand-millionth of an atmosphere, the amplitude being of the order of only one-thousand-millionth of a centimetre or about the wave-length of a penetrating X-ray.

* *Cf.* Fletcher, *Frank. Inst. Journ.*, **196**, 289, 1923.

The ear is, in fact, one of Nature's most sensitive devices.

As regards sensitiveness to changes of intensity, however, when two sounds of the same frequency are sounded alternately and the ear has matched them as being of equal loudness, it requires as much as 10 per cent. alteration in one before any loss of equality is detected. This figure applies to moderate and loud sounds, and increases to about 20 per cent. for faint sounds which have an intensity only about ten times that of the threshold or minimum energy of audibility. Fletcher found from these data that the total auditory range can be covered in not more than 270 steps, each one recognisable by the ear as just perceptibly louder than the one before it.

These figures relate to the best laboratory conditions: in ordinary circumstances the ear would not be so critical. For example, if even as little as two seconds elapse between successive sounds the sensitivity of the ear to loudness changes is halved. In consequence, it is convenient for practical purposes to regard the intensity range of the ear as covered by only 120 reasonably perceptible steps. Thus on the sensation scale 120 represents the range of the ear corresponding to the energy range of 10^{12}-fold mentioned above. This yields the convenient decimal relation that an n-fold increase in sound energy corresponds to a sensation change of $10 \log_{10} n$ steps.

To take an illustration, the threshold value of audibility is of importance in reverberation measurements as we shall presently see. Now a million times the threshold value is Sabine's standard initial intensity for such work. In other words, if on an energy scale the threshold audibility has a value

unity, Sabine's standard intensity has a value of one million. On the sensation scale, however, the associated loudnesses registered by the ear are determined by the logarithm of the values on the energy scale. Thus these loudnesses are 0 for the threshold audibility and 60 for the Sabine standard intensity. Incidentally the loudness of normal speech is about 60 upon the same sensation scale.

It has been established that over a wide range pure tones of different frequencies are judged to be equally loud when their amplitudes have equal ratios to the threshold values. The matter is not quite so simple for complex sounds, for when equally loud complex sounds are equally magnified they sometimes do not continue to appear equally loud. This means that the quality of speech sensations, for example, may depend somewhat upon the loudness.

The amount of distortion in the intensity of individual notes which is permissible in the reproduction of speech or music will naturally depend upon circumstances, and no accepted criteria seem to be available. However, if we may judge from threshold values, there are certain imperfections in the normal ear which probably set a limit beyond which accuracy of reproduction need not be carried. While it is true that, taking the average of several normal ears, the curve of threshold sensitiveness is fairly smooth over the frequency range, yet the threshold sensitiveness of a single normal ear is not uniform, but exhibits maxima and minima at certain frequencies peculiar to that particular ear. In a typical case ten-fold variations of energy sensitiveness occur as the frequency range is traversed. Different individuals have quite different

characteristics so that music does not apparently sound the same to different persons. Consequently, while the effect of altering the intensity of some component frequency might be detected, there would possibly be divergences of opinion as to the effect on the quality.

As regards the range of audible frequency, estimates of the lower limit by various observers vary from about 8 vibrations per second to 40 vibrations per second. The upper limit is fixed variously between about 12,000 and 35,000 vibrations per second.

Figures for the ability of the ear to detect perceptible change in frequency when two notes are sounded alternately indicate that within the range 500–4000 vibrations per second the ear can, on the average, detect a frequency change of about one-third of one per cent. For lower notes the sensitivity is less, and at 64 vibrations per second the minimum change which can be detected is practically one per cent.

Experiments have been conducted upon the masking effect of one sound upon the audibility of another. It has been found, in general, that a pure tone is more easily masked by a tone of lower pitch than by one of higher, though if the tones have adjacent pitches they easily mask each other.

The Characteristics of Speech and Music

The characteristics of speech * are also of importance in connection with the acoustics of auditoriums. In the first place the loudness of speech has some

* Fletcher, *Frank. Inst. Journ.*, **193,** 729, 1922.

bearing on its distinctness. Distinctness is best for ordinary loudness of conversation, under which conditions the oscillatory pressure (R.M.S.) in the sound-wave at one foot from the mouth appears to be about one dyne per sq. cm. This is about 1000 times as great as the minimum or threshold pressure necessary for audition, and about one-thousandth of the maximum that can be reached before tickling sensations and pain supervene in the ear. In energy units these values become one million and one-millionth respectively. Deviations from normal loudness by a ten-fold increase or decrease in amplitude have little effect upon distinctness, but a decrease in amplitude to one-hundredth is found on a telephonic test to reduce the intelligibility of isolated syllables to about 50 per cent.—a state which falls short of the 70 per cent. criterion usually taken by telephone engineers to represent the practical limit of intelligibility for speech. It is found that consonants are more seriously affected than vowels by reduction of speech intensity; and in ordinary conversation 50 per cent. of mistakes can be traced to confusion over three consonants alone.

As regards frequency, the main energy of the voice is, speaking broadly, of low pitch; the normal male voice has a very pronounced low-pitched constituent of frequency about 120 vibrations per second, while the female voice has one about an octave higher. However, while the energy of the voice is mostly of low pitch, the characteristics essential to intelligibility are carried by high-frequency sounds. For instance, if speech is passed through a filter which removes all sounds lower in

pitch than about 500 vibrations per second, 60 per cent. of the sound energy is removed, but, while the result is somewhat unnatural, the distinctness is practically unimpaired. But if frequencies above 2000 are eliminated, then, although less than 5 per cent. of the sound energy is removed, the percentage of unconnected syllables correctly interpreted by a hearer is reduced to about 75 per cent. Some of the consonants in speech, for example, the "hiss" sounds, have components of very high frequency, even above 4000. For distinctness of speech it is therefore vital to maintain adequate loudness of the high-pitched sounds, and thus preserve the vigour of the consonants.

These figures may be compared with those obtained by telephonic tests on speech transmission. From published data it would be anticipated that, to transmit speech naturally and distinctly, a telephone system must be capable of dealing satisfactorily with a frequency range of from 60 to 5000 vibrations per second. In practice, however, it is found that the somewhat narrower range from 200 to 4000 vibrations per second will serve almost as well. While there are speech frequencies outside the range 60 to 5000, the loss in naturalness and intelligibility occasioned by their absence is said to be slight. Further, within these frequency limits it is possible to amplify the energy of any one component of a sound nearly ten times before the ear can detect any departure in the quality of the transmitted speech. In the case of music a frequency range of about 35 to 7000 vibrations per second must be catered for.

The rate of emission of sound energy for con-

versational speech is about 125 ergs per second; for public speech, say about twenty times this amount; for a violin bowed forte about 600 ergs per second; for an open diapason organ pipe at wind-pressure 0·13 lb. per square inch, from 1400 to 32,000 ergs per second according to the pitch of the note.* These data, combined with reverberation equations given later (p. 67), give an idea of the intensity level at which sounds are usually heard.

How minute the energy used in speech is may be realised from an illustration due to Mr R. L. Jones of the Research Laboratories of the American Telephone and Telegraph Company, that if a million persons were to talk steadily, and the energy of their voices were to be converted into heat, they would have to talk for an hour and a half to produce enough heat to make a cup of tea!

* P. E. Sabine, *Phys. Rev.*, **21**, 475, 1923.

CHAPTER II

THE ACOUSTICS OF AUDITORIUMS

The Behaviour of Sound in a Closed Room *

We have already discussed the main facts relating to the production and transmission of sound, but it will assist in appreciating the conditions which must be satisfied to ensure satisfactory hearing in an auditorium if we briefly recapitulate the chief phenomena which arise when sound is emitted within a closed room.

The sound proceeds outwards from the source in expanding spherical waves which reach hearers or strike the boundaries of the room. At the boundaries they are enfeebled slightly or markedly, according to the nature of the surfaces, and thus enfeebled are in great part reflected in directions determined by the shape of the boundary concerned. The sound travels quickly, and so very soon through numerous successive reflections its energy is more or less uniformly diffused throughout the room, every element of volume being filled with waves proceeding in every direction.

If a sound-wave strikes an object which is small compared with the wave-length, the sound is scat-

* See W. C. Sabine, *Collected Papers on Acoustics* (Harvard Univ. Press), 1922; and Buckingham, *Bur. of Standards Sci. Papers*, No. 506, 1925.

tered rather than reflected in a definite direction, so that a complex sound may not be reflected with exactly its original quality. The scattering does not reduce the total sound in the room, but merely tends to promote its more uniform distribution.

Sound is a form of energy, and once produced in a confined space it will continue until it is transmitted by the boundary walls or transformed into some other kind of energy, generally heat. The absorption at the boundaries may be very low so that, for example, in a small empty room at the National Physical Laboratory a word spoken in an ordinary tone of voice is audible for as long as seven seconds afterwards. With more absorbent wall surfaces the aerial vibrations are damped out by frictional conversion into heat within the pores of the surfaces, and the sound decays more quickly. The sustained echo or reverberation—as it is called—is then less prolonged.

If the source of sound is continuously maintained the loudness in the room increases until the rate of emission of sound from the source is balanced by the absorption of the surfaces. A steady state is then reached in which the loudness at a given point is generally greater than it would be under like conditions in the open air. While on the whole the loudness will be greater near the source than farther away, the general distribution will be more uniform than it would be in open air, owing to the random diffusion of the sound which at any moment has already suffered repeated reflection. The tendency to uniformity will be impaired if the shape of the boundary is such as to focus incident waves unduly, an effect which is most marked when there are large smooth surfaces with pronounced curvature.

But, as previously remarked, apart from focussing effects, the general tendency to uniformity and enhanced loudness may be modified by interference phenomena, with the result that throughout the room there may be regions of unusual loudness and regions of comparative silence or "dead spots." When a source of fairly high pitch is sounded in a room the system of stationary waves or nodes and antinodes is readily detected, particularly if one ear is stopped up. If the note is sufficiently pure, it is possible to find a position in which the unstopped ear can detect practically no sound. The positions of maxima and minima, however, depend upon the frequency of the note, and so for complex sounds the quality heard will depend upon the position of the ear. The use of both ears ordinarily tends to obscure the detection of interference effects in a room.

Finally, resonance phenomena may affect the nature of the sound heard. The boundaries of the room may resonate, and in that event the effects of their vibration will be specially pronounced for notes of certain pitch. Resonant materials near the source may well enhance its loudness, just as the sound from a tuning-fork is enhanced by the proximity of a resonator. Resonant partitions at a distance may similarly display selective absorption; for example, when organ music is played in a church, pews and floors vibrate in this manner and thus absorb some of the energy of the sound.

Resonance may also be caused by the air in the room, each room having a definite pitch to which it responds. In a large room the fundamental resonance is of low pitch, but smaller rooms and alcoves

respond to higher pitch, as may readily be demonstrated by singing up and down the scale.

Acoustical Demands in an Auditorium *

The essential features of good acoustics in an auditorium are:—

(*a*) The sound should everywhere be sufficiently loud.

(*b*) The "quality" should be preserved, *i.e.* the proper relative intensities of the several components of a complex sound should be maintained.

(*c*) The successive syllables or sounds of rapid speech or music should be clear and distinct, *i.e.* without undue overlapping.

(*d*) There should be freedom from extraneous noises.

These apparently simple conditions cannot all be expressed in physical terms. For instance, in the case of music some prolongation and blending of successive tones are usually desired, and the degree to which freedom from overlapping is satisfactory is a matter of personal preference.

Before we can apply the above conditions to the design of an auditorium we must determine in measurable form the architectural features by which the acoustic condition of a hall may be varied. In so far as questions of preference arise, we must then obtain the opinion of persons of accepted critical taste as to the most desirable conditions. The factors involved on the engineering side are the shape

* See W. C. Sabine, *Collected Papers on Acoustics*, 1922; Sutherland, *Science Progress*, **171**, 101, 1922; Davis, *Architect's Journ.*, **63**, 565, 1926; Kaye, *Building*, **1**, 406, 1926; *Nature*, **119**, 603, 1927.

of the auditorium, its dimensions, the materials of its surfaces, and, as regards extraneous noise, the sound-proofing of its construction.

Expressing the essentials for good hearing in terms which bear a closer relation to the engineering side of the problem, we may say that the chief conditions are:—

(*a*) There should be no perceptible echoes.

(*b*) The loudness should be adequate and uniform throughout the building, *i.e.* the sound should not be focussed to some regions to the detriment of others.

(*c*) There should be no undue reverberation, *i.e.* each sound should die away quickly enough to be unobjectionable by the time the next is emitted.

(*d*) The hall should be as uniformly reverberant as possible for musical sounds of all pitches, and should be devoid of marked resonances.

(*e*) The walls should be adequately sound-proof.

In studying the acoustic demands in auditorium design we have therefore to consider questions of shape and echo, of general reverberation, of interference and resonance, and of sound-proofing. These fundamental questions are dealt with in turn in the following chapters.

CHAPTER III

LOUDNESS AND ECHOES

Loudness and Seating Arrangements

THE question of the adequate loudness of a given source, as heard in the remoter parts of a room, will naturally depend upon its size; and the size of the room should accordingly be limited by the purpose for which it is to be used—for instance, a hall suitable for an orchestra will normally be too large for the unassisted voice. The question of the suitable size of an orchestra for a particular hall is dealt with on p. 142.

As regards speech, according to some experiments made by Saunders * a century or so ago in still open air, the voice of a person reading aloud carries about 90 ft. forwards, 30 ft. backwards, and 75 ft. on each side. These distances appear to be somewhat excessive for voices of moderate strength, and experience rather supports the judgment of Sir Christopher Wren,† who in a letter on church-building lays down as the standard that guided him: "A moderate voice may be heard 50 ft. in front of a preacher, 30 ft. on each side, and 20 ft. behind the pulpit, and not this unless the pronunciation be distinct."

We may take it that for voices of moderate

* T. Roger Smith, *Acoustics of Public Buildings*, p. 33, 1861.

† Wren, *Parentalia*, p. 318.

strength, hearers should be at distances not much greater than about 50 ft., and that they should have a direct view of the speaker, so that they can then receive an uninterrupted "ray" of sound.

These requirements usually lead to raked or stepped seating, the rake or degree of steepness of the rows of seats depending on the purpose of the auditorium. For instance, if it is essential for the auditors to be able to look down on a table as in an experimental lecture theatre, the steepness of the seating has to be more pronounced than is necessary in, say, a theatre or music-hall where the stage is lifted above the nearest seats, or in a church where the high pulpit obviates the necessity for a raked floor. The Lecture Theatre of the Royal Institution, illustrated on p. 130, presents a floor of the first type, but much earlier examples are, of course, afforded by the Greek theatre or the Roman amphitheatre. In some of the latter the rake of the seats increases as they become more remote from the arena. These points are dealt with later.

Echoes and General Shape

The focussing of sound is associated with the presence of large and markedly curved smooth surfaces, such as a dome or barrel vaulting, which are preferably avoided from an acoustic point of view. A hall with an approximately rectangular section may be relied upon to give a satisfactory distribution of sound.

With regard to echoes, experience agrees that they are not noticeable when the time-interval between the direct and reflected sounds is less than about

one-fifteenth of a second; or, in other words, when the path difference is less than about 75 ft. In fact, it may be considered that reflected sounds (even if not quite of the original quality) arriving within this interval will contribute usefully in raising the level of loudness of speech, whereas those arriving later are undesirable and should be enfeebled as far as possible by absorption or scattering. Thus the question of echoes will not arise except with large halls, and is likely to be specially pronounced in the presence of smooth concave surfaces, though even a slight echo may sometimes be the cause of poor acoustics. It is important, therefore, that such reflecting surfaces should be rendered absorbent and suitably broken up, so that the sound is no longer strongly reflected, but enfeebled and scattered. One method of achieving this is to coffer the ceiling and walls, and to render the panels of the coffering absorbent.

Study of the Shape of an Auditorium

In reviewing the acoustic properties of a proposed building it is necessary, therefore, to assess the plans from the above points of view. If the building is intended for speech it should first be considered whether hearers are all placed at reasonable distances from and within sight of the speaker. If the hall is large, one must study the shape of the building, determine whether any undesirable echoes, focussing, or other reflections will occur, and arrange if possible that sounds reaching remote seats shall be strengthened by reflections from suitable situations. Further, if, as is usually the case with a large hall, calculation

shows that it will be necessary to introduce considerable areas of absorbent materials to prevent excessive reverberation, their disposition and shape can be so chosen that they will not only reduce general reverberation, but will also assist in suppressing undesirable reflections.

The complete determination in three dimensions of the possible echoes and focussing effects in an auditorium would be a complicated matter. It is possible, however, in most cases, to obtain very useful information from a study of sections. Caution must, of course, be exercised where interference phenomena are prominently involved, but for a building of rectangular section or other simple design interference effects are likely to be only of subsidiary importance in music, and, in the case of speech, of no importance at all.

There are three main methods of studying the reflecting characteristics of sections:—

1. The geometrical method.
2. The sound-pulse method.
3. The ripple-tank method.

In the first method the general directions of likely echoes are deduced from simple geometry based upon the usual optical laws of reflection. The method is apt to be somewhat tedious if the effect of much detail is to be investigated. Further, as we have seen (p. 2), sound may spread by diffraction outside the limits imposed by geometrical optics, and the second and third methods, applied experimentally to scale models, have the advantage of revealing not only the optical reflections, but also the spreading that may occur when pulses or short

trains of sound-waves are concerned. The experimental methods are particularly convenient for tracing the progress of a sound through a series of positions, and incidentally are more convincing when for any reason it is desired to display the results.

1. *Geometrical Method.*

The geometrical method may thus be used as a first approximation for predicting the general direc-

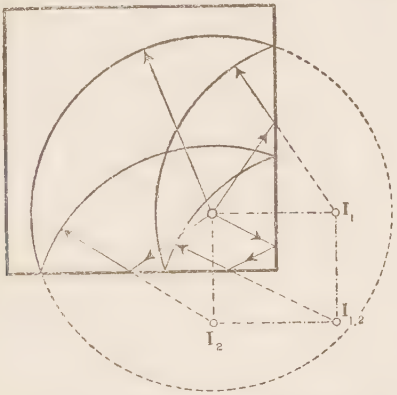

Fig. 20.—Wave-front of sound from source within a rectangular boundary after reflections from walls.

tion of likely echoes upon the basis of the usual optical laws of reflection, remembering that in interpreting the results, particularly in the case of complicated shapes, sound may spread somewhat outside the limits thus obtained.

Fig. 20 shows the various portions of the wave-front for a simple case, namely, a source of sound 0 situated within a hollow rectangular section. If the boundaries had been absent the wave would have reached the position of the dotted circle. As

matters are, the total path from the source to any point on the several parts of the wave-front is equal to the radius of this circle. The images of 0 in the various walls are indicated.

Fig. 21 represents a case worked out on geometrical principles by Michel *: it relates to a vertical longitudinal section of the Leipzig Gewandhaus famed for its acoustic excellence. The source of the sound

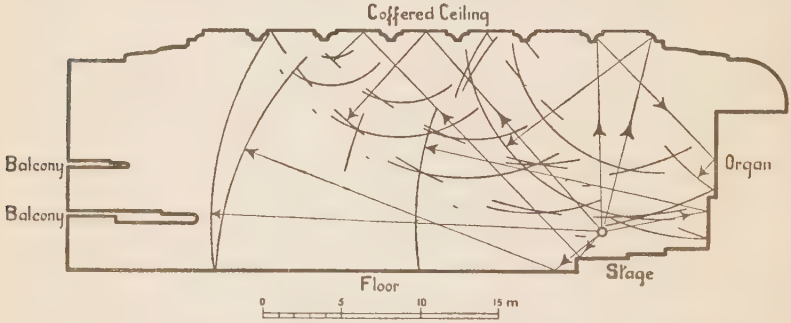

Fig. 21.—Longitudinal section of Leipzig Gewandhaus. Geometrical tracing of sound-waves at 25 metres from source 0 (Michel).

is at 0. The positions and tracks of the sound-waves for a path distance of 25 metres from the source are shown. Among them is the unreflected part of the wave, the remainder of the wave being broken up by reflections from the walls, floor, and coffered ceiling. It should be added that the diagram gives no indication of the relative intensities of the various portions of the wave-front.

Fig. 22 is the corresponding diagram for a transverse vertical section of the same building for the same path distance. For simplicity, the reflections from the left wall are not shown.

* Michel, *Hörsamkeit Grosser Räume* (Vieweg u Söhn, Braunschweig), 1921.

Fig. 23 is a study by the geometrical method of the acoustic behaviour of four types of ceilings.

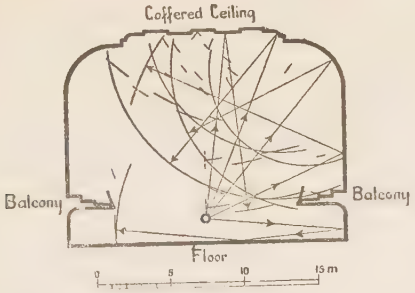

Fig. 22.—Transverse section (through source) of Leipzig Gewandhaus. Geometrical tracing of sound-waves at 25 metres from source. Reflections from left wall not shown (Michel).

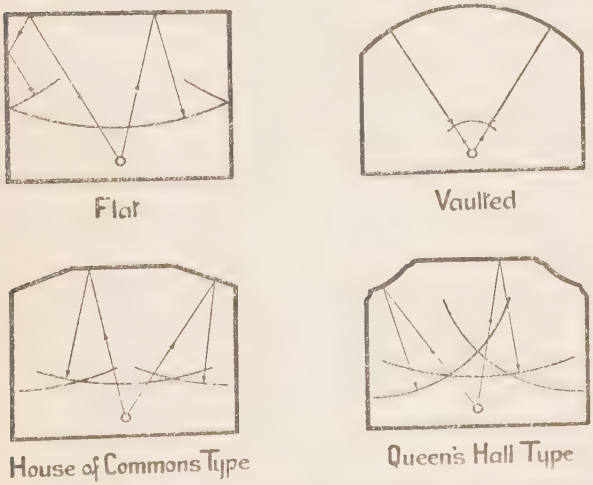

Fig. 23.—Geometrical analysis of acoustic features of different types of ceilings.

As will be seen, the simple rectangular pattern gives satisfactory results, not notably inferior to those of the two different types of splayed ceiling styled "House of Commons" and "Queen's Hall," which

serve to augment the sound in the side galleries. If the number of splays is increased indefinitely, it becomes the barrel vault which, if the curvature is sufficiently pronounced as in Fig. 23, where the speaker is at the centre of curvature of the ceiling, results in objectionable focussing effects. A good general rule is that, if a curved ceiling is preferred, its radius of curvature should not be less than twice the height of the hall. A similar remark applies to curved walls in relation to the corresponding dimensions of the hall.

2. *Sound-pulse Method.*

The reflecting characteristics of the shapes of sections of auditoriums can be demonstrated experimentally by visual or photographic observation of the progress of an actual sound-pulse within a model section having open sides. This was first carried out by the late Professor W. C. Sabine* in 1913, some of whose photographs revealed cases where the spreading of sound outside the limits of optical reflection was a matter of some importance.

For this photography of sound-waves Sabine adopted the general technique which had been developed previously by various physicists, notably Töpler (1867),† Dvořák (1880),‡ Mach (1881),§ Boys (1891),‖ and Foley (1912).¶ As the sound-pulse spread in the model, Sabine illuminated it instantaneously by light from a distant electric

* W. C. Sabine, *Collected Papers on Acoustics*, p. 180, 1922.
† Töpler, *Ann. d. Phys.*, **131,** 33, 1867.
‡ Dvořák, *Ann. d. Phys.*, p. 502, 1880.
§ Mach, *Ann. d. Phys.*, **159,** 330, 1876 ; **41,** 140, 1890.
‖ Boys, *Nature*, **47,** 415 and 440, 1893.
¶ Foley and Souder, *Phys. Rev.*, **35,** 373, 1912.

spark. This light, after passing through the model section, fell upon a photographic plate. Light is refracted by sound-waves—just as it is by convection currents above hot flames or radiators—and the position of the wave in the model was consequently clearly recorded on the photograph.

Foley * has recently described the form of apparatus at present in use at the Sabine Laboratory (p. 182). With this apparatus the very short time-interval between the production of the sound-pulse and its illumination on the photographic plate is controlled by a high-speed rifle bullet in flight. The rifle-bullet method of controlling the longer time-intervals has, however, the disadvantage that it is impracticable to fire a projectile for every wave when one is making visual instead of photographic observations.

Fig. 24 shows a sound-pulse apparatus set up at the National Physical Laboratory.† Foley's earlier technique is followed with certain modifications to ensure steadiness of the time intervals. A large electrical machine capable of generating a potential of about 100,000 volts charges a battery of five Leyden jars C_1, C_1 on each side of the machine. By means of trigger spark-gaps the jars are discharged at will through the two spark-gaps marked "sound-spark" and "light-spark," both within a light tight box. The sparks pass in the trigger-gaps when the glass plates shown are moved in or out of the gaps. The spark passing between the platinum electrodes of the "sound-spark" generates a sound-pulse—somewhat intensified by the small

* Foley, *Am. Architect and Architectural Review*, Nov. 8, 1922.
† Davis and Fleming, *Journ. Sci. Insts.*, **3**, 393, 1926.

Leyden jar C_2—and this is illuminated a small fraction of a second later by light from the delayed "light-spark," the delay being effected by means of a large condenser C_3 across the electrodes. The light-spark is enclosed within a small capillary tube, a point-source affording good definition being thus

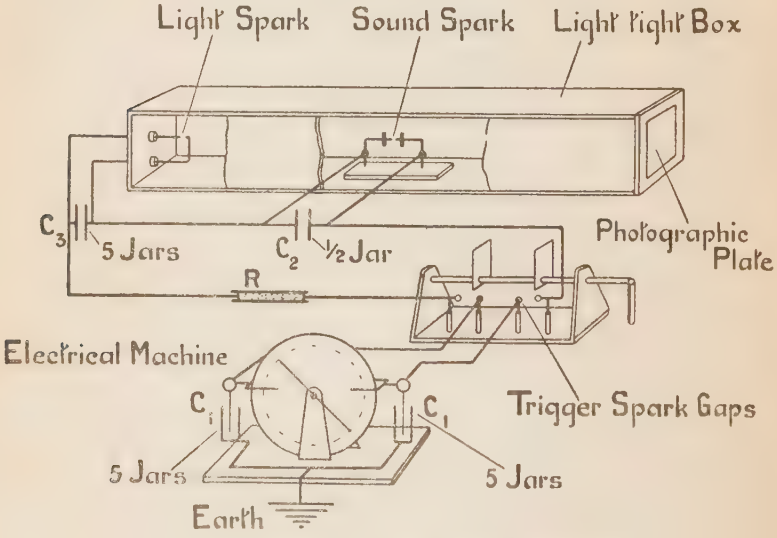

FIG. 24.—Apparatus for sound-pulse photography.

obtained. The electrodes are of magnesium, so that the illumination is especially brilliant and photographically active. The light from the light-spark casts a "shadow" of the sound-pulse upon a viewing screen or photographic plate at the end of the box. The model section of the building of which the reflecting characteristics are desired is made in ebonite or hard wood, usually to a scale of 1 in. to 32 ft. The sound spark-gap is suitably disposed within the interior of the section and at right angles to its plane.

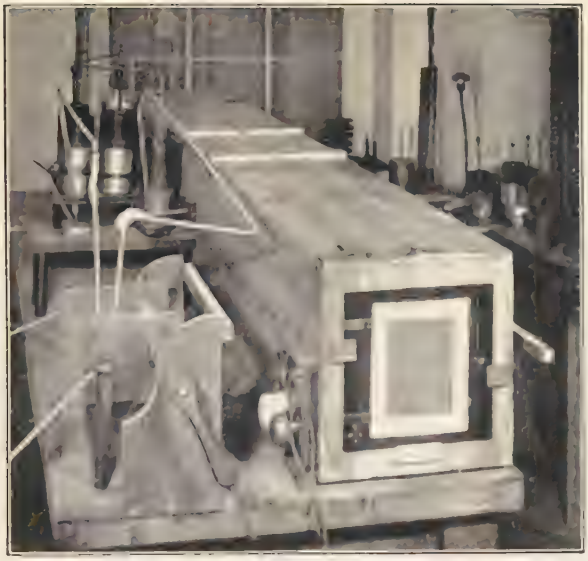

FIG. 25.

FIG. 26.

Figs. 25 and 26 are photographs of N.P.L. apparatus for sound-pulse photography. See p. 53.

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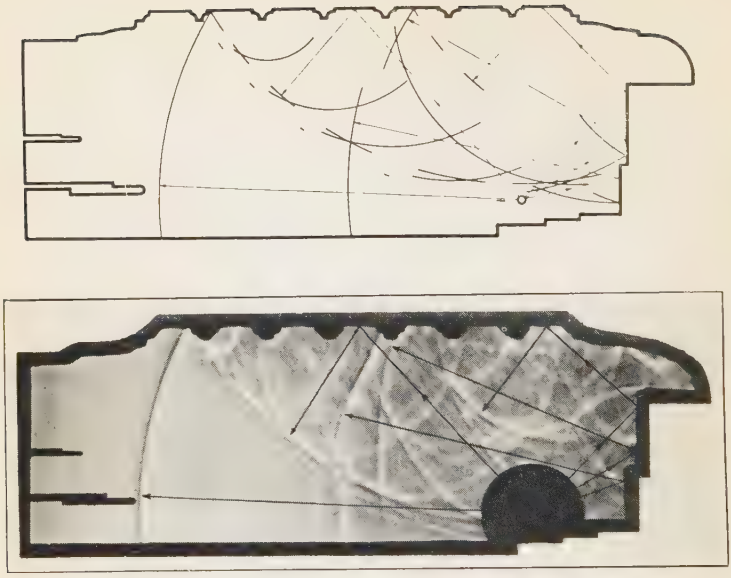

FIG. 27.—Comparative studies by the geometrical and sound-pulse methods of the Leipzig Gewandhaus (longitudinal section). See p. 53.

FIG. 29.—Sound-pulse photographs illustrating effect of modifying design of a theatre ceiling (Sabine). See p. 54.

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Constancy in the behaviour of the apparatus is increased by passing a series of sparks at a regular rate for some time before the photographic negative is exposed. The liquid rheostat *R*, first suggested by Huguenard, improves the control of the longer time-intervals, although it somewhat enfeebles the sparks. In order to prevent fogging of the plate by light scattered from the inner surface of the box, the interior is painted dead black and is fitted with a series of diaphragms, the apertures of which increase from the light-spark to the plate. Light from the sound-spark is prevented from reaching the plate by projecting discs mounted on the electrodes.

The apparatus, as at present designed, is capable of giving photographs showing the progress of waves up to a time-interval corresponding to about one-eighth second in an actual full-size building, *i.e.* to a path distance of, say, 150 ft. Figs. 25 and 26, Plate V, are two photographs of the N.P.L. apparatus.

In Fig. 27, Plate VI, a photograph taken of an actual sound-pulse (emitted from a source indicated by the small circle) at the National Physical Laboratory, is compared with Michel's corresponding geometrical study of the reflecting characteristics of the vertical section of the Leipzig Gewandhaus. For simplicity all reflections from the floor and the stage have been omitted from Michel's drawing, and were avoided in the sound-pulse photograph by removing the floor from the model. For ease of interpretation the tracks of a number of "rays" have been added to the figures. The important point brought out is that, while the geometrical method indicates the nature and general direction of reflections, the sound-pulse actually spreads considerably

beyond the limits imposed by the laws of geometrical optics.

Fig. 28, Plate VII, is another example due to Mr Fleming, which displays the scattering effect of coffering in a curved ceiling. The first photograph shows a spherical wave originating at the focus of the ceiling, so that in the absence of the coffering this should give rise to a flat wave-front on reflection. The two succeeding photographs show that much sound is scattered towards the side walls by each recess in the ceiling, the descending wave-front being correspondingly attenuated.

Fig. 29, Plate VI, illustrates two designs of the Scollay Theatre examined by W. C. Sabine. The essential point to be observed is that in the first photograph there is a pronounced ceiling reflection which would reach the lower parts of the two balconies so late as to be troublesome: in the second photograph the ceiling has been modified and the troublesome echo is scattered and so enfeebled.

Fig. 30, Plate VIII, taken at the National Physical Laboratory shows a set of illustrations relating to a sectional model of an auditorium, with two different types of galleries, the floor being totally absorbent and the ceiling low enough to provide a strong reflected beam within one-fifteenth second of the original sound. The first photograph shows the outgoing wave spreading uniformly in all directions from a position of a speaker near the centre of the floor of the chamber. The second shows the conditions after reflections have taken place from the ceiling and from the walls below the galleries. The third and fourth photographs record further progress of the waves.

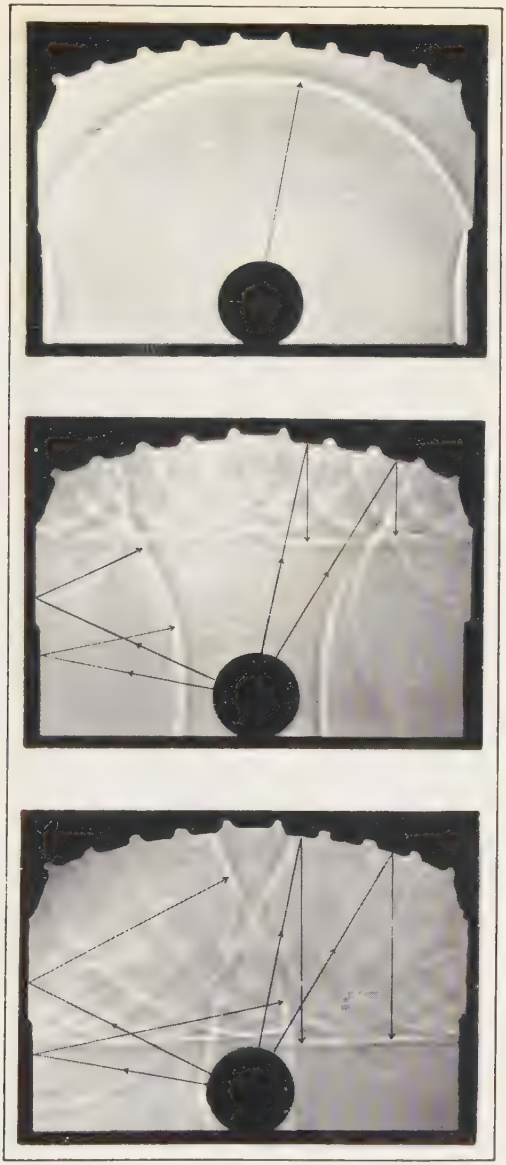

FIG. 28.—Sound-pulse study of attenuated reflection from a coffered ceiling. See p. 54.

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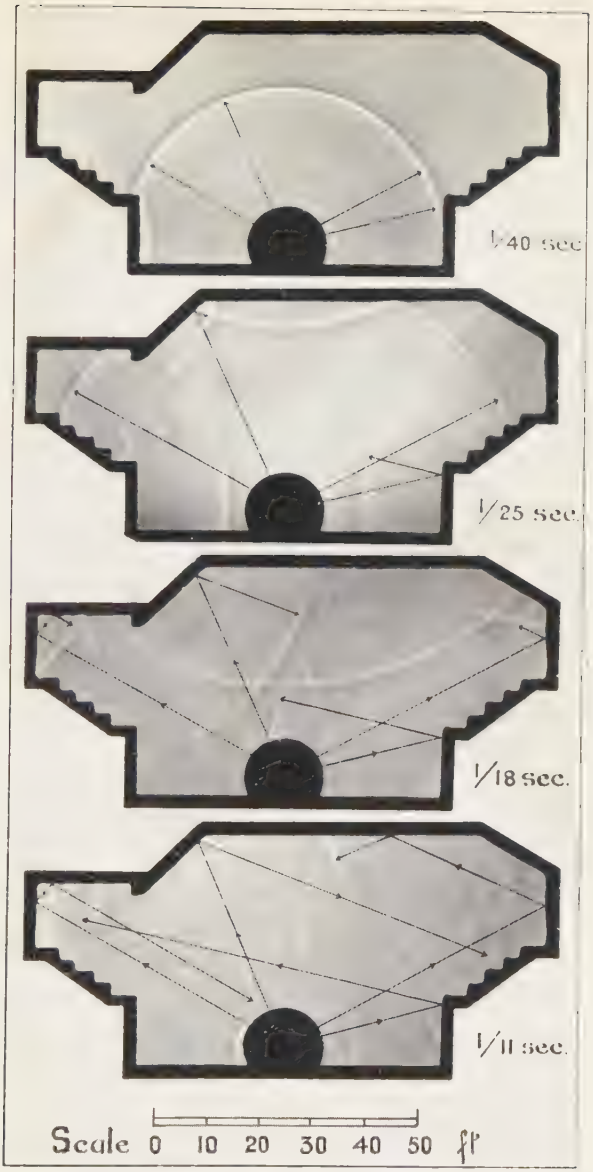

FIG. 30.—Photographs showing successive stages in the progress of a sound pulse in a sectional model of an auditorium with two different types of galleries. See p. 54.

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It will be noted that the right-hand gallery, which is under the main ceiling, receives a pronounced ceiling reflection which will serve to reinforce the direct sound, whereas the left-hand gallery, which is in an alcove, is deprived of the advantage of the strong ceiling reflection (*cf.* Fig. 34, Plate XI). A further point is that waves reflected from the back walls of the galleries proceed upwards and are finally returned to the floor from the ceiling as rather late reflections. Such reflections should be suppressed and the upper parts of the walls are thus generally suitable for the application of sound-absorbing materials.

3. *Ripple-tank Method.*

The ripple-tank method is based on the fact that ripples in a small tank are found to be suitable for illustrating acoustical phenomena, the wave-length being usually comparable with the size of any models concerned.

Lagrange, Scott Russell,* and Lamb † have remarked on the close similarity between the equations dealing with the propagation of cylindrical waves of sound in air and those dealing with the propagation on the surface of an inviscid liquid of certain gravity waves in which surface-tension plays no appreciable part. In the case of ripples in a small tank, however, surface-tension becomes important, and the analogy loses its generality, for, whereas the velocity in the case of sound is independent of the wave-length, in the case of ripples there is a marked dependence. However, the analogy is still perfect for small

* Scott Russell, *B.A. Report*, p. 331, 1844.
† Lamb, *Hydrodynamics*, 5th edit., Arts. 189; 172, 1924.

maintained ripples of simple harmonic type provided the depth of liquid is greater than one-half the wave-length, and experiments outside the limits of strict mathematical analogy show that impulsive ripples, despite the subsidiary wavelets that accompany them, bear a striking general correspondence to impulsive sound-waves.*

As early as 1843 we find Scott Russell,† in connection with the acoustics of buildings, referring to the study of the behaviour of sound by using the water-wave analogy. Watson‡ and Michel§ have studied the acoustical features of buildings by means of ripple-tank experiments. The method has the advantage of giving visual demonstration of the actual progress of waves, and its adaptability and the ease and rapidity with which the effect of modifications can be examined are of special value.

The general arrangement adopted at the National Physical Laboratory is shown in Fig. 31, Plate IX, where a model outline of a longitudinal section of a hall (made in wood on a scale of $\frac{1}{4}$ in. to 1 ft.) can be seen lying flat on the glass bottom of a shallow tank of water about 2 cm. deep. The floor of the hall is on the left, the ceiling on the right, and the galleries in between. The reflecting characteristics of the outline of the section are observed from its behaviour towards ripples produced by means of a plunger just dipping into the water at a point corresponding to a position of a speaker standing near the centre of the floor of the hall. The plunger is not operated

* Davis, *Phys. Soc. Proc.*, **38**, 234, 1926.
† Scott Russell, *B.A. Report*, p. 96, 1843.
‡ Watson, *Acoustics of Buildings*, p. 12, 1923.
§ Michel, *Hörsamkeit Grosser Räume*, 1921.

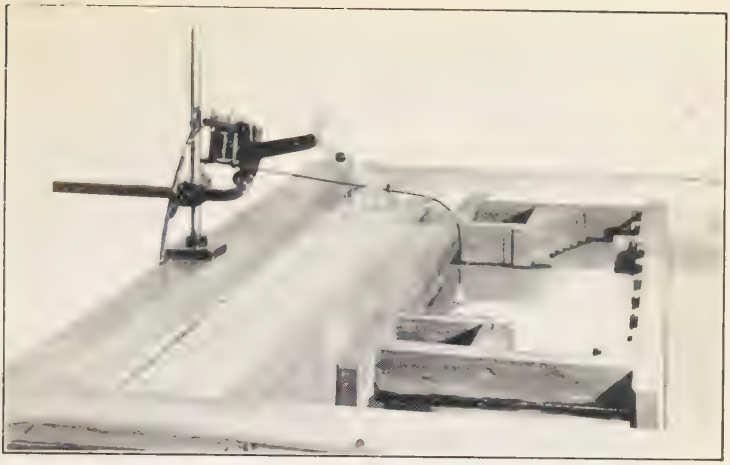

FIG. 31.—N.P.L. ripple-tank apparatus showing sectional model of auditorium in position. See p. 56.

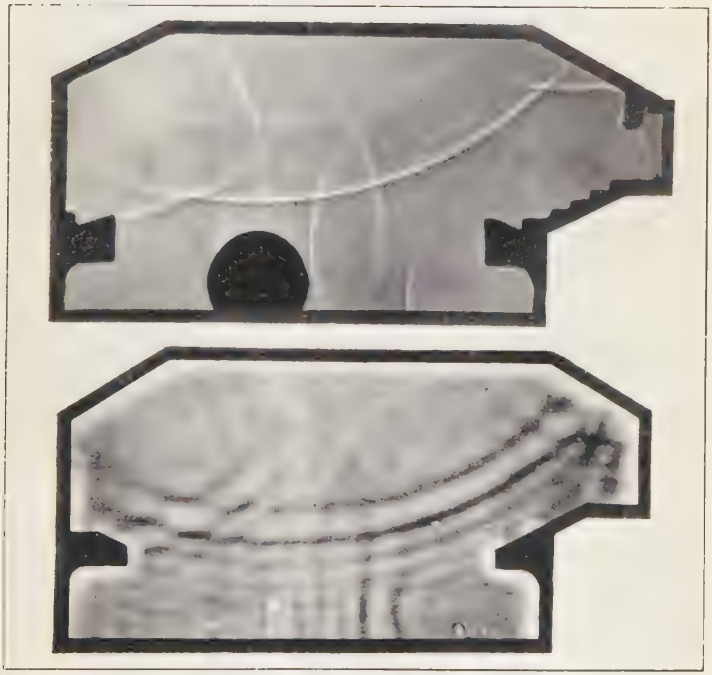

FIG. 32. Comparative studies showing resemblance between sound-pulse and ripple photographs for similar model sections. See p. 57.

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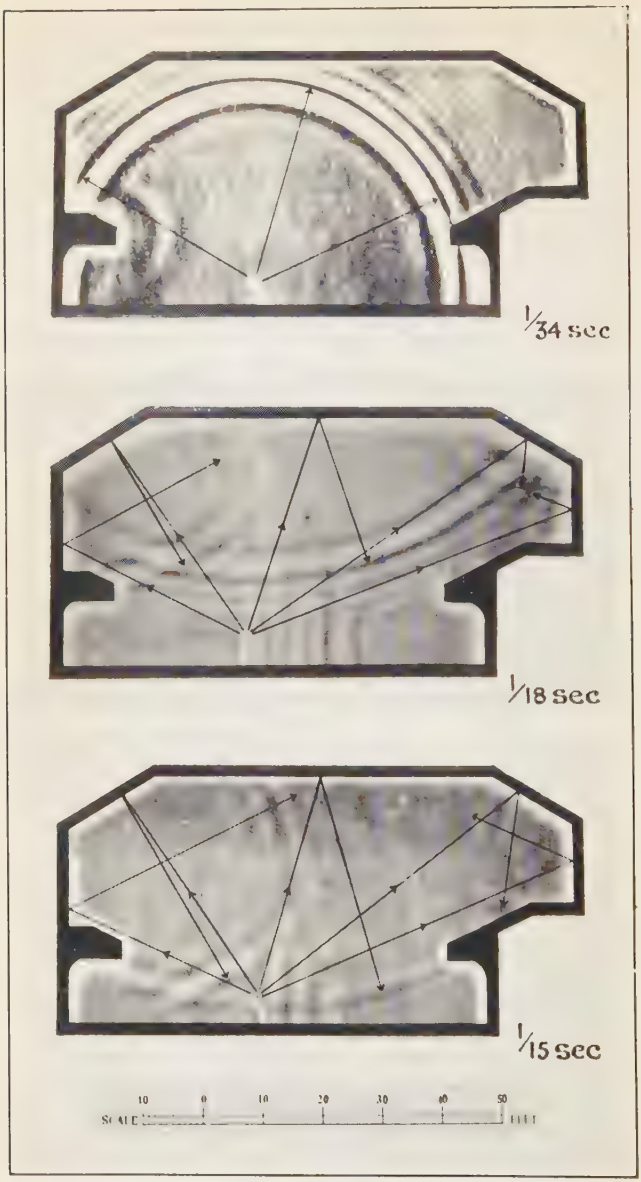

FIG. 33.—Showing successive stages in the progress of ripples within a sectional model of an auditorium. See p. 57.

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continuously, but is merely withdrawn from the water by means of an electromagnetic device, and it thus originates a short train of waves which proceed outwards in circles and are reflected at the wooden boundaries of the model. To facilitate study of the progress of the waves, light from an arc lamp passes upwards through the glass bottom of the ripple tank and casts a shadow of the waves upon a screen suitably mounted above. In some cases there is a slight advantage in floating a thin film of oil over the surface of the water. A sloping "beach" at the edges of the tank serves to extinguish reflected waves. By taking snapshots at suitable times, photographs of selected features may be obtained. The model is afterwards photographed in position with the tank empty, thus avoiding a blurred outline.

Fig. 32, Plate IX, compares a ripple photograph with a sound-pulse photograph in similar circumstances. The position of the speaker—indicated in each case by a circle—is much the same, and the distances travelled by the waves correspond almost exactly. The sound-pulse photograph is much clearer because it deals with only a single pulse instead of a short train of waves, but when this is recognised the correspondence between the two photographs is most striking, not only as regards the main ceiling reflection, but as regards the extent and direction of reflections from subsidiary surfaces.

Fig. 33, Plate X, shows a sequence of photographs of an auditorium much on the same lines as those in Fig. 30, Plate VIII, the floor being totally absorbent. The distance from crest to crest between successive ripples corresponds to sound-waves of length from

$1\frac{1}{2}$ ft. to $4\frac{1}{2}$ ft. in the actual full-scale building, *i.e.* sounds having a frequency of from 250–700 per second, an important region in the speech range.

The photographs are most easily interpreted if attention is directed to the progress of only one of the waves of the train. To isolate such a wave, note may be made on each photograph of all the several parts of the disturbance which have traversed the same total distance from the source. As an illustration in Fig. 33 the various parts of the wave and their tracks are indicated.

The photographs of Fig. 33 show that acoustically the section is fairly satisfactory. As regards echo effects, we may note the dimensions of the hall are such that nearly all the sounds which are but once-reflected reach hearers within one-fifteenth second of the original sound. It will be seen, however, that just as in Fig. 30, reflections from the backs of the galleries are directed upwards towards the ceiling, whence by reflection they will reach the floor too late to reinforce the original sound.

In Fig. 34, Plate XI, the section is compared with an altered form in which the roof has been modified so that the right-hand gallery is now under a separate ceiling. Waves have been photographed at corresponding moments for the two cases, and, whereas in the original section part of the pronounced ceiling reflection is directed towards the gallery, in the modified section this useful component no longer reaches the back of the gallery owing to its reflection by the splayed ceiling back to the main body of the hall (*cf.* Fig. 30, Plate VIII).

For some purposes it is helpful to have a record of the complete progress of a wave. This is possible

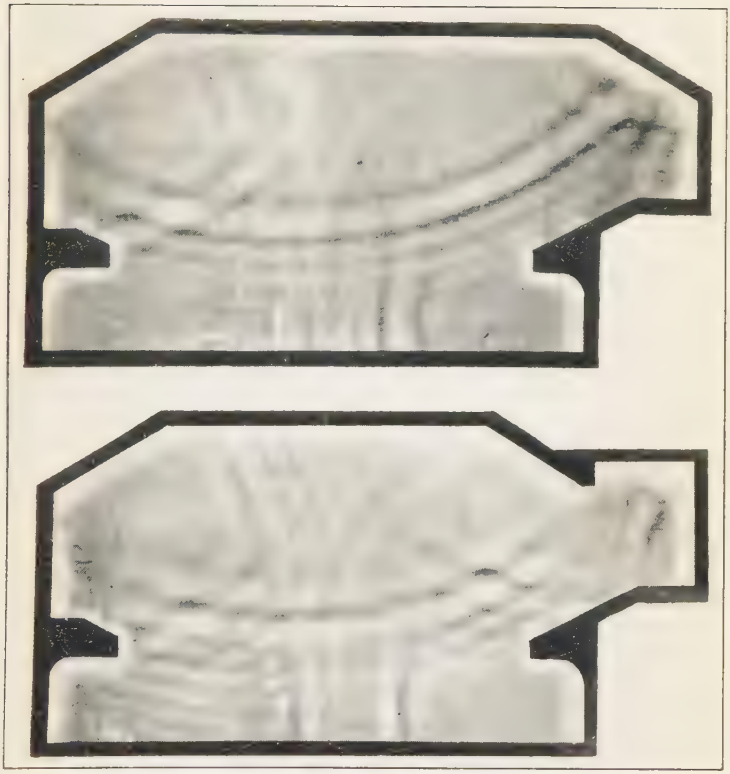


FIG. 34. Ripple photographs contrasting ceiling reflections on right-hand gallery for two different types of gallery ceiling. See p. 58.

[*To face page* 58.

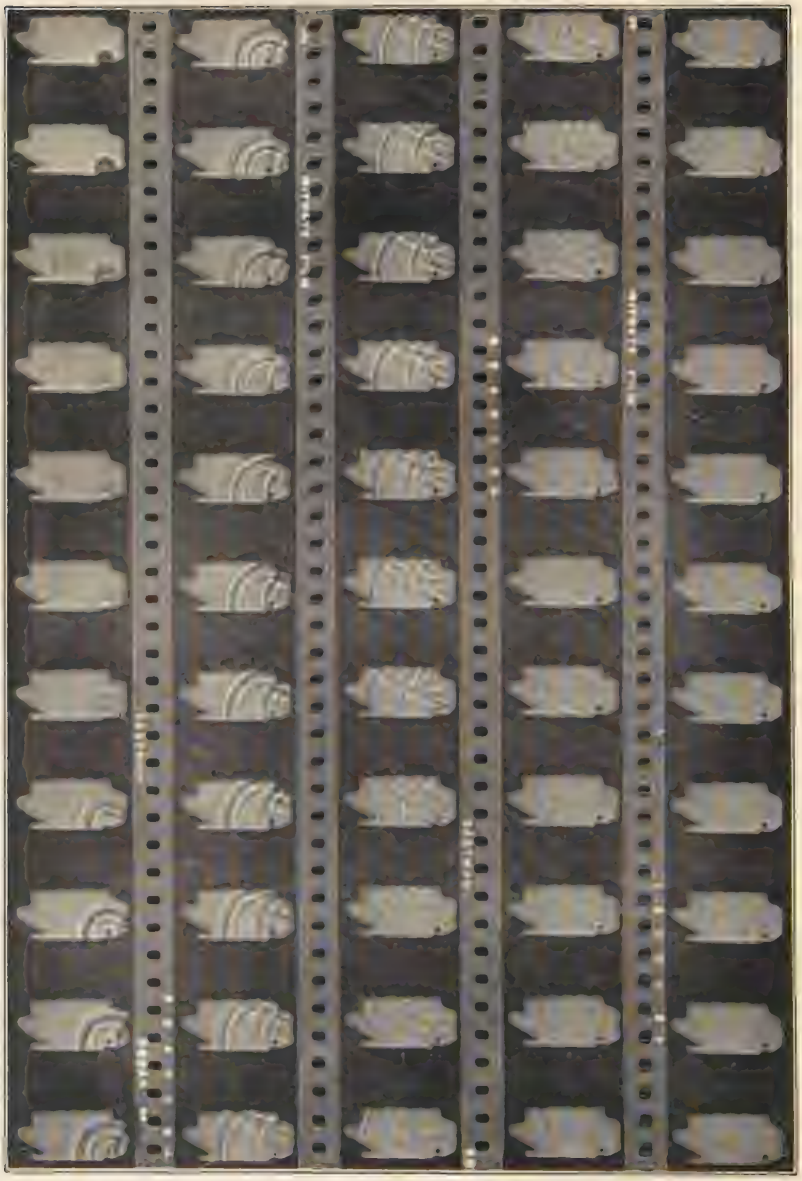


FIG. 35.—Kinematograph photographs of progress of ripples within a sectional model of an auditorium. See p. 59.

(To face page 59

by the aid of a kinematograph camera. Fig. 35, Plate XII, shows an example.

Three-Dimensional Study.

The study of echoes within a three-dimensional model presents especial difficulties and, up to the present, does not appear to have been undertaken. Such an investigation appears to be desirable when the shape of the building is so complicated that treatment by sections is unlikely to be satisfactory. By producing an impulsive sound in the model at the position of the speaker, it should be possible with recording apparatus to observe in any given position the time-interval between the reception of the original sound and of echoes.

Watson * describes a ray method by which he traced out the reflections of a high-pitched sound in a completed auditorium at the University of Illinois. The ticks of a watch were directed by means of a reflector to certain walls, and the echoes were clearly located, the watch ticks being heard distinctly in the path of the beam even at 80 ft. from the source. Later a metronome was used enclosed in a sound-proof structure with only one opening, the sound being directed by means of a horn.

Finally Watson used the hiss from an alternating arc-light placed at the focus of a parabolic reflector. The light from the arc reduced the labour of locating the sound echoes. These high-pitched sounds differ from those of speech or music, but tests by observers in the auditorium, when music and speeches were

* Watson, *Bull. No. 73 of University of Illinois Engineering Experiment Station.*

rendered, verified the general conclusions obtained with the arc-light.

It should be reiterated, however, that the wave-

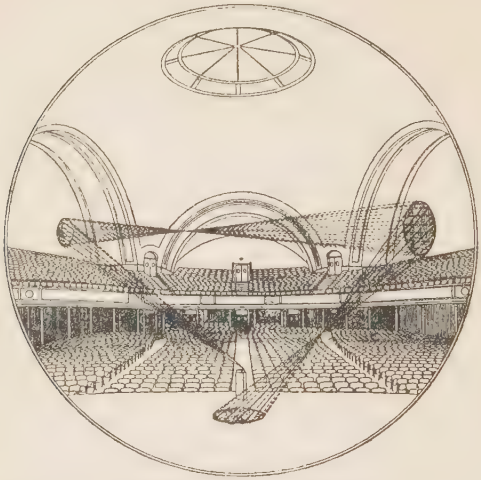


Fig. 36.—Illustrating a three-dimensional survey (ignoring diffraction effects) of an echo in an actual auditorium (Watson).

length of a sound is usually so great that spreading owing to diffraction effects is pronounced. Sound would not be closely confined to regions indicated by ray methods. Fig. 36 is an illustration of Watson's survey of the auditorium mentioned.

CHAPTER IV

REVERBERATION

It has long been recognised that the most frequent acoustical defect met with in large auditoriums is excessive reverberation, that is, the continuous echo or undue persistence of sound within a room owing to insufficient absorption by the boundaries. A little reverberation is pleasing and helpful for both audience and speaker (or singer), but excess causes confusing overlapping of successive sounds or syllables. It is not that the audience fails to hear, but fails to analyse the medley of sound. Raising the intensity of the source does not help matters, rather does it enhance the confusion.

Historical

As early as 1835 in a *British Association Report* we find Reid * recognising reverberation to be the most prevalent acoustical defect, and pointing out that it could be reduced by making the walls more absorbent by increasing their roughness or irregularity or by hanging draperies. He particularly stressed the need to exclude superfluous space, the importance of which will be clearer later.

Dickens, in Chapter ix of *Martin Chuzzlewit* (1843), in his description of the locality in which

* Reid, *B.A. Report*, p. 13, 1835.

Todger's Boarding House was situated, wrote: "these mansions, now only used for storehouses, were dark and dull, and, being filled with wool, and cotton, and the like—such heavy merchandise as stifles sound and stops the throat of echo—had an air of palpable deadness about them."

Roger Smith,* in his *Acoustics of Public Buildings* (1861), remarked that, "In empty houses a great reverberation is perceptible, which diminishes as the floors are covered with carpets and the rooms filled with furniture."

Tyndall, in 1868, in evidence before a Select Committee of the House of Commons stressed the value of a low ceiling as a reinforcing device, and the influence of an audience and of draperies in quenching the after-sound. During the proceedings of this Committee it was elicited that flock paper applied to the walls of a reverberant room had proved an effective remedy.

Again, Johnstone Stoney (1885) † described an experiment in which he tested a room having its walls papered over a lining of canvas, the canvas being a short distance (from one-eighth to a quarter of an inch) in front of the framework over which it was stretched. From his experiment he inferred that concert halls or public rooms could be effectually freed from echo effects by the simple expedient of lining the walls and ceiling in such a manner. He states that the canvas may be papered or distempered, or painted so that there need not even be any change in the room visible to the eye.

It is evident that it was clearly realised nearly a

* Smith, *Acoustics of Public Buildings*, p. 50.

† Johnstone Stoney, *Roy. Dub. Soc. Proc.*, **4**, 53, 1885.

century ago in this country that the remedy for excessive reverberation in a room is to introduce a sufficient area of sound-absorbing material.

Rayleigh * in the 2nd edition of his *Theory of Sound* (1896) gave the first mathematical treatment of the absorption of sound at the face of a rigid porous surface. If the surface is not rigid, naturally there is absorption due to the vibrations set up. If it is rigid, sound-waves penetrate into the pores of the material, and in this restricted space are dissipated into heat through viscous and allied actions. When the depth of the capillary channels is small compared with the wave-length, but large relative to the diameter, Rayleigh showed on certain assumptions that the absorbing power of unit area of a rigid porous surface is given by

$$a=\frac{4M}{2M^2+2M+1}$$

where

$$M=\frac{2(1+g)\sqrt{\nu\gamma}}{r\sqrt{n}}$$

g=ratio of unperforated to perforated area of the porous surface.
ν=kinematic viscosity of the gas.
γ=ratio of the specific heats of the gas.
r=radius of pores (assumed cylindrical).
$n=2\pi\times$frequency.

Rayleigh pointed out that the equation holds good only if the radius of the pores is sufficiently small to allow free exchange of heat between the air and the sides of the channels, and estimated that if r

* Rayleigh, *Theory of Sound*, 2nd edit., 2, 328 (Macmillan), 1896.

exceeds 0·01 cm. the equation is invalid. Adopting reasonable values for the variables in Rayleigh's formula, it appears that the absorbing power of a non-yielding porous wall should be approximately proportional to the square root of the frequency of the sound.

While Rayleigh's object was the discussion of the mechanism of this special case of absorption, he clearly recognised that prolonged reverberation seems inevitable in large spaces bounded by non-porous walls, roof, and floor, and with few windows. Obstacles, as such, do not destroy sound. In the absence of dissipating forces what is not transmitted must be reflected. Destruction of sound depends upon viscosity and thermal conductivity, and the effectiveness of these agencies is enormously augmented by contact with solid matter exposing a large surface. At such a surface tangential motion, as well as normal motion, is hindered and a passage of heat to and fro takes place between the air and the solid. So rapid are the alternations that their influences extend only to a very thin layer of the air and of the solid and are thus greatly favoured by a fine state of division. Rayleigh goes on to recommend that the mitigating effect of thick carpets should be utilised as a remedy for reverberation, and that, in addition, similar material should be applied to the walls and ceiling.

It is, however, only in more recent years that any systematic attempt has been made to determine on a large scale the absorbing power of materials and, before building an auditorium, to calculate the amount of absorbent which must be introduced to ensure an acceptable reverberant condition. Before

proceeding to a description of this work, and in order to appreciate the manner in which the reverberant state of a room may be controlled and the optimum condition expressed, it is desirable to consider briefly the theoretical and experimental considerations upon which reverberation work is based.*

Theory

Theories of reverberation have been given by W. C. Sabine (1900) †, Franklin (1903) ‡, Jaeger, (1911) §, and Buckingham (1925).‖ In all cases it is recognised that a sound in an ordinary room suffers some two or three hundred reflections before it finally dies away; and it is assumed that, in consequence, through random arrangement, the sound energy rapidly becomes uniformly distributed throughout the enclosure. Interference phenomena are ignored, and we shall see later that they cause but little inconvenience in reverberation work. It must, however, be understood that the several reverberation formulæ which follow are valid only to the extent to which the neglect of interference is justifiable.

While Sabine should, of course, be regarded as the pioneer in quantitative reverberation experiments and the associated theoretical work, Jaeger's analysis is in some respects more comprehensive, and it will be convenient briefly to outline the theory here with special reference to his presentation. The

* Davis, *Phil. Mag.*, **2,** 543, 1926.
† W. C. Sabine, *Collected Papers on Acoustics*, p. 1, 1922.
‡ Franklin, *Phys. Rev.*, **16,** 372, 1903.
§ Jaeger, *Akad. Wiss. Wien. Sitz. Ber.*, **120,** 2*a*, 613, 1911.
‖ Buckingham, *Bur. Stands. Sci. Paper*, No. 506, 1925.

analysis may be summarised as follows: Sound-waves emitted from a simple uniform source of sound in an enclosed space proceed outwards and suffer reflection and absorption at the various enclosing surfaces. If on an average for these surfaces a fraction, a, of the energy of the incident sound is absorbed on incidence and the remainder reflected, and if for each ray of sound the number of incidences upon the surfaces is n per second, and if the mean intensity of the sound (*i.e.* energy per unit volume) in the room at a given instant is I, then the change of intensity by absorption at the surfaces in a time dt is

$$dI = -I.a.n.dt.$$

This assumes that a does not depend on I—an assumption which appears to be justifiable under ordinary conditions (*cf.* p. 92).

By a statistical method Jaeger showed that for a ray of sound in a closed room the mean number of reflections per second is given by

$$n = vS/4V$$

where

V = total volume of room.
S = total surface of room.
v = velocity of sound.

If E denotes the uniform rate of emission of sound from the source, the rate of energy change in unit volume of the room is given by

$$\frac{dI}{dt} = \frac{E}{V} - \frac{vaSI}{4V} \quad . \quad . \quad . \quad (1)$$

This is the fundamental differential equation in reverberation work. The following solutions of

this equation relate to the special circumstances stated:—

1. If a uniform source of sound in a room is started at a given instant, the intensity I in the room after a time t is given by

$$I=\frac{4E}{vaS}(1-e^{-vaSt/4V}) \quad . \quad . \quad (2)$$

2. The intensity in the room ultimately reaches a steady state I_{max} which is given by

$$I_{max}=\frac{4E}{vaS} \quad . \quad . \quad . \quad (3)$$

3. If the emission of sound is suddenly stopped after the intensity in the room has attained the steady state, the intensity I at a time t after stopping the source is given by

$$\begin{aligned} I&=I_{max}e^{-vaSt/4V} \\ &=\frac{4E}{vaS}e^{-vaSt/4V} \quad . \quad . \quad . \quad (4) \end{aligned}$$

Following Sabine, who expressed much of his work in terms of the time taken for a sound to die away from the steady state to the threshold of audibility, and adopted as his standard initial condition an intensity I_{max} equal to one million times the threshold value,* we have from (4)

$$10^{-6}=e^{-vaSt/4V},$$

whence, if T is this "standard" duration of audibility, we have

$$T=\frac{55{\cdot}2V}{vaS}.$$

* This corresponds approximately to the loudness near a speaker adapting his voice to a fairly large room. See p. 33.

Thus on theoretical grounds alone we have the standard reverberation period T for sound in air as (giving v its accepted value):—

$$T=0{\cdot}05V/aS \text{ in foot seconds units} \quad . \quad (5)$$

or

$$T=0{\cdot}162V/aS \text{ in metre seconds units} \quad . \quad (6)$$

Equations (5) and (6) are those which are used in practical reverberation problems, and T is an important acoustical characteristic of a building.

The total absorbing power, aS, is of course equal to the sum of the absorbing powers of the component parts of the total surface S, so that if there are in the room surfaces S_1, S_2, S_3, etc., having respectively absorption coefficients a_1, a_2, a_3, etc., then

$$aS=a_1S_1+a_2S_2+a_3S_3+\ldots$$

Sabine's own theoretical treatment established that the intensity I at a time t after stopping the sound emission during the steady state is given by

$$I=(E/VA)e^{-At}.$$

He further calculated that A is related to the mean free path of sound (p) in the room by the equation $p=av/A$. If, therefore, we recognise that p has the statistical value $4V/S$ calculated by Jaeger, Sabine's equation becomes identical with (4).

The reverberation equations show that for a given activity of source the general intensity of reverberant sound within a room is weakened by increasing either the area S of the surfaces or their average absorption coefficient a. It follows that introducing objects—including people—into a room will reduce the maximum intensity of the sound attained.

From equation (5) the duration of audibility T

decreases when the absorbing power or area of the exposed surfaces is increased, but increases when the volume is increased. Since the volume V cannot be altered without at the same time altering the surface S, the ratio V/S is important in determining T. Hence the effect of increasing the irregularities of the boundary of a room is to reduce the reverberation. Further, for rooms of similar shape V/S is proportional to the linear dimensions, so that large rooms tend to exhibit prolonged reverberation. It follows that, to secure high intensity of sound together with short reverberation, rooms of restricted dimensions are necessary.

Experimental Work on Reverberation

The most important experimental work on reverberation is that of the late Professor W. C. Sabine of Harvard University, which was published from time to time between 1900 and 1915. As the greater part of his papers appeared in a number of different architectural journals, the physical basis of the work was not set out very fully.

Sabine's first investigation (in 1895) was that of a lecture room in the Fogg Art Museum at Harvard, the acoustics of which were so bad that the room was almost unusable. He proceeded to study the decay of sound in the room from a steady source which was suddenly stopped. Sabine first attempted to use instrumental means for the purpose, but finally decided to measure the duration of audibility as perceived by the ear, *i.e.* the time required for the sound to decay from its initial intensity to the threshold intensity.

The source of sound was a single organ pipe. Extraneous noises led to irregularities in the observed duration of residual audibility, but these were largely reduced by working at night when greater stillness prevailed. If the conditions were satisfactory the accuracy of the observations proved to be surprisingly good. Sabine states that in a particular example individual values differed from the mean of 20 observations by not more than 0·31 second in any case. The estimated probable error of a mean of 20 observations was 0·02 second: in 10 means the maximum deviation from the mean of the 10 was only 0·05 second. Moreover, the values obtained were reproducible. For example, observations taken every few nights for two months in the Fogg Museum Lecture Room gave reverberation values varying from 5·45 to 5·62 seconds, with a mean of 5·57 seconds, a result which was again obtained after the lapse of one, and then of three years.

The Laws of Reverberation.

Sabine subsequently conducted an extensive series of experiments to elucidate the laws of reverberation. Preliminary experiments established the important point that the observed duration of reverberation was almost independent of the positions of the source and of the observer within the room.

The next point established was that the effect of a given amount of absorbent was practically independent of its position. For example, in the case of the lecture room of the Fogg Museum referred to above, where the initial period of reverberation was 5·57 seconds, 270 metres of cretonne cloth reduced

the period to 3·25 seconds when draped on a scaffolding under a low ceiling at the back of the lecture room, and to 3·29 seconds when hung fully exposed in the high dome-like central ceiling.

The remaining point to be settled was the relation between the reverberation period of a room and the absorbing power of its exposed surfaces. Sabine realised that as regards the processes at the boundary, it was unnecessary to distinguish between the dissipation of the energy of sound into heat and its transmission into outside space. He therefore chose an open window as his standard unit of absorption. As a practical unit, however, it is not convenient, owing to the extraneous noises which habitually enter a room through an open window except perhaps on very still nights in winter. Consequently, Sabine worked with cushions and expressed his results in open-window units. In this way he found the absorbing power of an open window to be proportional to the area of the aperture.

Sabine next proceeded to study the relation between the duration of reverberation t and the exposed area X of introduced cushions in a number of different rooms ranging in volume from 65 to 9300 cubic metres. He found that for a given initial intensity the results for each of the rooms could be represented approximately by a rectangular hyperbola such that $(X+C)t=k$, where k was a constant depending on the initial intensity, and the constant C obviously represented the initial absorbing power of the empty room expressed in terms of area of cushions. A selection of such curves is shown in Fig. 37: curves 1 and 2 are on one scale and 3 and 4 on a second. The continuous part of

each curve represents the region explored experimentally. When the curves for the different rooms were compared the parameter k was found to be proportional to the volume V of the room and (taking one square metre of open window as the unit of absorption) to be given by

$$k/V = 0{\cdot}171 \text{ in metre seconds units,}$$

so that

$$t = 0{\cdot}171\,V/(X+C).$$

Now, since the value of k depends upon the initial intensity of the sound, it was necessary to ascertain

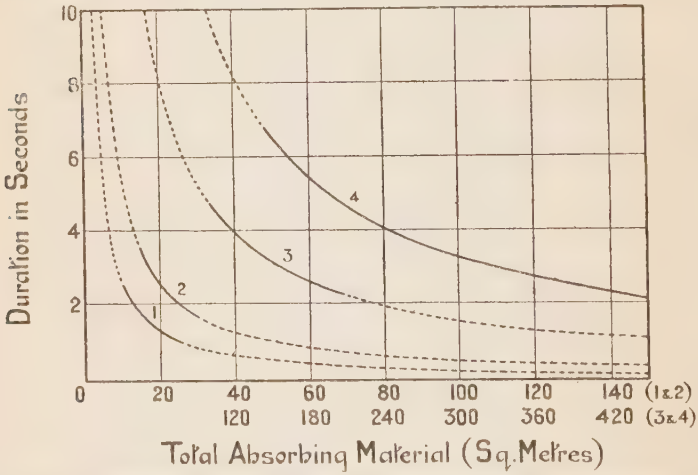


Fig. 37.—Relation between duration of audibility and total absorbing power for four rooms of different volumes (Sabine).

the value of this initial intensity. This Sabine did as follows: Four similar organ pipes were placed in the room, the distances of separation being, he states, sufficient to prevent any mutual action between them. In these circumstances the energy emission from four pipes is equal to four times that from a single pipe. The observed increase in the

duration of audibility when four pipes are used instead of one gives the time in which reverberant sound in the room decays four-fold. By conducting a series of experiments with 1, 2, 3, and 4 pipes, Sabine showed that the sound decayed logarithmically. Having thus ascertained the rate of decay and so calibrated the room, Sabine was enabled to calculate the reverberation period for the standard initial intensity which, as already stated, was chosen to be one million times the threshold intensity. The results showed that the calculated period did not agree with that observed, the discrepancy being dependent on the amount of absorbent present. In other words, the initial intensity of the sound was reduced by introducing absorbents, and when the appropriate correction was made, the above value of k/V became 0·164 for the standard intensity of $I=10^6 i_0$. Thus Sabine's experiments gave for the time of reverberation under standard conditions

$$T=0{\cdot}164V/(X+C)$$

which may be written

$$T=0{\cdot}164V/aS \text{ in metre seconds units} \quad . \quad (7)$$

The close relation which this empirical formula bears to that deduced in equation (6) on p. 68 from theoretical considerations is most striking: it is good evidence for the fundamental assumption that reverberant sound energy may be treated as uniformly diffused throughout a simple room, both as regards position and direction of motion. The close agreement also implies that under satisfactory conditions Sabine's open-window standard has an absorption coefficient which is almost exactly unity. It is probable that, if this was not the case, Sabine would

not have found the absorbing power to be proportional to the window aperture.

Reverberation Measurements of Absorption.

It is evident that reverberation measurements afford a means of ascertaining the absorbing power of unit area of a given material. Two methods are possible. The first employs direct substitution, *i.e.* ascertaining the area of open window which gives the same reduction of reverberation as a known area of test material. Alternatively, by the use of the formula (5) or (6) on p. 68, one may find from the change in the reverberation period the increase in the absorbing power of the room associated with the introduction of the test material. Actually this second method is an indirect substitution method, for the constant of the formula used was established by open-window calibration.

In such measurements it is necessary to make sure that the experiments are carried out under conditions in which the fundamental assumptions are justifiable. To this end, results should be obtained under varied conditions, and should prove to be independent of the position of the source, of the observer, and of the absorbent material.

Data for the absorbing power contributed by each exposed square foot of wood, glass, plaster, and certain other materials have been given by Sabine. They vary from 1·0 for each square foot of open window or of the floor space covered by an audience as ordinarily seated, 0·5 per square foot for hair felt 1 in. thick, 0·2 per square foot for certain curtains, to 0·01–0·03 for glass or hard plaster.

Each isolated member of an audience is equivalent in absorbing power to about $4\frac{1}{2}$ sq. ft. of open window. A more complete discussion of absorption measurements by reverberation methods is given later, with a table of results (pp. 90 and 112).

The Optimum Value of the Reverberation Period

A variety of experiments have been carried out by different observers to determine the degree of reverberation best suited to music and to speech in rooms of various sizes. It is obviously essential that there should be some reasonable concensus of opinion on this point, and accordingly W. C. Sabine * made a study of the degree of unanimity of cultivated musical taste.

The first experiments were carried out with piano music at the New England Conservatory of Music, which contains a number of small practice-rooms of different sizes (ranging from about 2000 to 6000 cu. ft.). In order to ascertain the acoustical condition which would meet the requirements of those who were to use the rooms, Sabine arranged that the reverberation could be varied by introducing absorbent cushions. A committee of three musical experts listened to a varied selection of music from the same piano in each of the rooms in turn, and the number of cushions was adjusted until the committee declared the room to be neither too "dead" nor too "reverberant."

The individual times of reverberation of five rooms when the acoustics were declared satisfactory were then measured for the same pitch and found to be 0·95, 1·10, 1·10, 1·09, 1·16 second, with a mean of

* W. C. Sabine, *Collected Papers on Acoustics*, p. 69, 1922.

1·08 second. The results show a gratifying agreement in musical taste, the maximum departure from the mean being only 0·13 second, and the average departure as low as 0·05 second.

There could be no question of prejudice in the results, for the committee were given no explanation of the nature of the experiments or of the effects of reverberation. The rooms were of different sizes; the final number of cushions required varied from room to room; in three cases the final accepted condition was approached from the direction of "under-reverberance," in two cases from the opposite direction.

The pitch of the note used is not specified in Sabine's paper, but probably his results relate to the organ pipe of the gemshorn stop, c^{ii} (512), with which much of his earlier work was conducted.

The above experiment relates only to the optimum reverberation for piano music in rooms of moderate size. Other experimenters have dealt with rooms of greater dimensions, and with the optimum condition for speech.

Eckhardt's Reverberation Curves for Speech.

On the basis of the fundamental reverberation equations given on p. 67, Eckhardt * has discussed the optimum reverberant condition for speech, and has displayed his calculations in an instructive series of curves illustrating the manner in which the acoustic condition of a room affects the growth and decay of intensity when sound is emitted in syllabic form.

When a uniform source of sound commences to

* Eckhardt, *Frank. Inst. Journ.*, **195,** 799, 1923.

emit energy in a room of moderate size, the average intensity gradually rises to a maximum or saturation value according to a curve such as that shown in the first part of Fig. 38. If the source is then stopped, the intensity decays in the manner indicated by the downward curve, which is the previous curve inverted.

The effect the absorbing power of the walls has

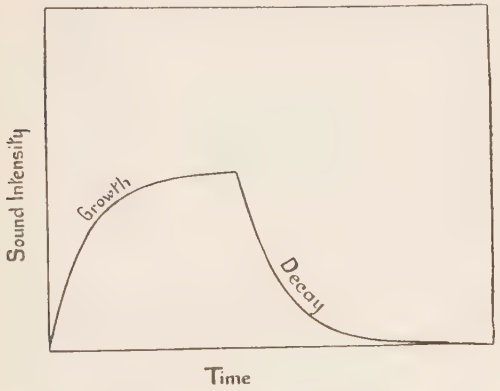


Fig. 38.—Curve illustrating growth and decay of reverberant sound within a room.

upon the rise of intensity in the room is illustrated in Fig. 39, which relates to a room of 1000 cubic metres volume. The rate of emission assumed for the source is that associated with the average speaking voice. The curves cover the range from the smallest to the largest absorption coefficients practically realisable. It will be seen that, for a small absorption coefficient, the intensity rises slowly towards a high maximum; while for a large absorption coefficient the intensity rises rapidly towards a lower maximum.

The effect of increasing the volume of a room,

while retaining walls with the same absorption coefficient, is to decrease both the rate of rise of intensity and the maximum intensity attained in the steady state.

In the case of speech, the emission is discontinuous, a usual rate being about five syllables per second.

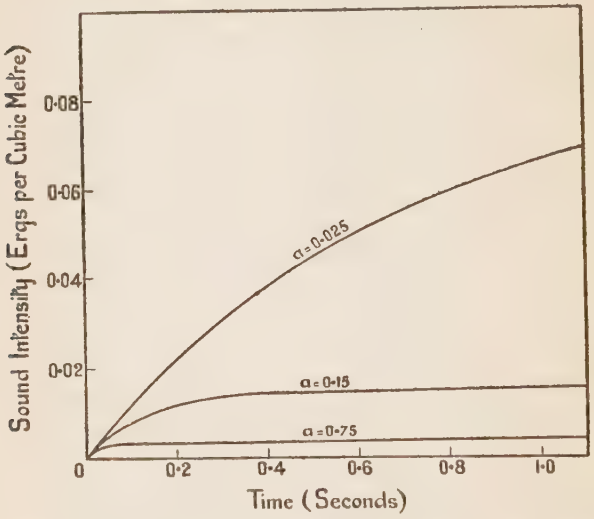


Fig. 39.—Curves showing growth of reverberant sound within a room for three different values of absorbing power.

Figs. 40, 41, and 42 show the growth and decay of sounds emitted at this rate in three rooms of the same size, but of different absorbing power. It is assumed that successive syllables are separated by intervals of one-twentieth second during which no sound is emitted. The resultant intensity time-curve for the room is obtained in each case by adding the effects of all the syllables, and is shown by the heavy line. The upper dotted curve shows the intensity which would obtain for continuous emission at a corresponding rate.

Fig 40, where the absorbing power is low, indicates a piling-up of sound and a relatively small intensity change between syllables, which leads to indistinctness. Improvement would result from a slower

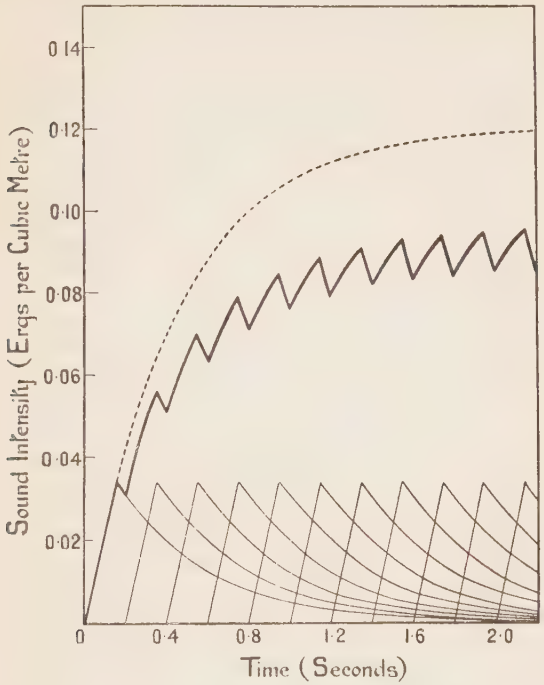


Fig. 40.—Reverberation curve for syllabic speech in a room of low absorbing power (Eckhardt).

pace by the speaker. The pace could even be so slow as to appear disjointed to the speaker, and yet the audience would not receive this impression.

In Fig. 41 the absorbing power of the surfaces has been chosen to give the most satisfactory acoustical conditions, according to the standards to be discussed shortly. In Fig. 42 the absorbing power is excessive, the reverberation period being only about

one-third of a second. Articulation in this latter case would be more distinct than in the condition pre-

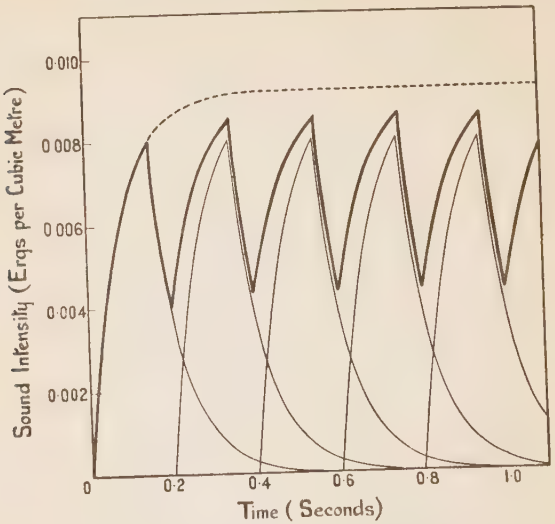


FIG. 41.—Reverberation curve for syllabic speech in a room of medium absorbing power (Eckhardt).

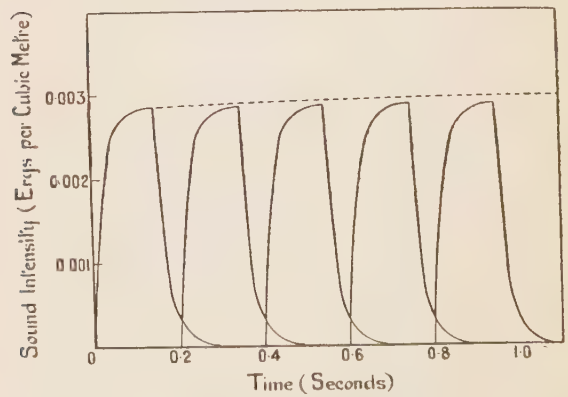


FIG. 42.—Reverberation curve for syllabic speech in a room of high absorbing power (Eckhardt).

viously mentioned as satisfactory, but it will be noted that the intensity is reduced. It is not clear why

this condition is not usually regarded as an improvement, but it would seem that the advantage of a more complete isolation of the syllables is more than counterbalanced by the reduction in loudness. On the other hand, such non-reverberant conditions rarely occur in practice (being the case, to some extent, of the broadcasting studio and incidentally of the padded room), and it may be that the effects, being somewhat unfamiliar to the ear, impress the observer as unnatural.

Preferred Reverberation Conditions.

A number of observers have made estimates of the preferred reverberation conditions of halls of various sizes as regards the hearing of speech and also of music. It has already been mentioned that W. C. Sabine found a period of just over one second to be the most acceptable for piano music in rooms of moderate size. Sabine was afterwards called in as acoustic consultant for the proposed Boston Concert Hall. Taking the Leipzig Gewandhaus (see Table IV) with a reverberation period of 2·3 seconds (maximum audience) as providing ideal conditions for orchestral music, Sabine * prescribed the same period for the proposed hall, an auditorium of different shape and materials and half as large again (with a volume of 650,000 cu. ft.). The acoustics of the building when erected proved entirely satisfactory and served as a confirmation of Sabine's reverberation formula.

From his subsequent treatment of the Little Theatre in New York it is evident that Sabine considered a period of 1·1 to 1·5 seconds as satisfactory

* W. C. Sabine, *Collected Papers on Acoustics*, p. 60, 1922.

for speech in a theatre having a volume of about 60,000 cu. ft., and that in his view a period of 2·2 seconds, while inferior, would not be specially questioned by the public.

P. E. Sabine * considers that "the time of reverberation of an auditorium with its maximum audience should lie between 1 and 2 seconds. For speech and light music it should fall in the lower half of this range, while for music of the 'larger' sort it may lie nearer the upper limit."

On the other hand, Lifshitz † does not differentiate between speech, singing, and instrumental music, as regards the optimum period of reverberation. He finds, for example, that for rooms having a volume less than 12,000 cu. ft. the optimum periods for speech, singing, and orchestral music agree to within 0·05 second, the mean being 1·03 second. For larger rooms he gives a relation between the optimum period and the volume, the graphical form of which is included in Fig. 44. Lifshitz finds that excessive reverberation is more tolerable for music than for speech, and that insufficient reverberation is less tolerable for music than for speech.

It should be realised that Lifshitz's test for speech was based upon quality, rather than distinctness. He recognised that decreased reverberation increased the clearness of speech, but was prejudicial to quality.

Lifshitz studied a number of halls in Moscow; his results are given in Table III.

The reason why longer reverberation is preferred in very large halls is not altogether clear. However, to reduce the period of reverberation of very large

* P. E. Sabine, *Am. Architect*, June 18, 1924.

† Lifshitz, *Phys. Rev.*, **25,** 391, 1925 ; **27,** 618, 1926.

auditoriums to about one second, it would usually be necessary to cover the ceiling and most of the wall area with thick felt or the like, and the intensity of sound in such a room would then be very weak. Presumably, therefore, in very large halls the persistence of sound is tolerated for the sake of the increased loudness, and speakers are expected to enunciate more slowly to accommodate themselves to the conditions.

TABLE III.—REVERBERATION IN VARIOUS HALLS (LIFSHITZ)

	Volume.	Seating capacity.	Reverberation.		Acoustics as regards speech and music.
			Empty.	Full.	
	Cu. ft.	Persons.	Secs.	Secs.	
Column Hall of House of Unions.	443,000	1600	3·55	1·75	Considered perfect when full, particularly for music.
Small Hall of the Conservatoire.	90,000	550	3·46	1·30	One of the best small halls in Moscow.
Big Hall of the Conservatoire.	600,000	2150	4·60	2·00	Reverberation excessive and sound somewhat loud.
Big Theatre .	490,000	2300	2·06	1·55	Empty, too reverberant. Full, sounds too "dead." Best with one-third audience.

F. R. Watson * has presented in graphical form the acoustic data of a number of auditoriums pro-

* Watson, *Frank. Inst. Journ.*, **198**, 73, 1924.

nounced good by public opinion. Watson differentiates between concert halls—used for music only—and auditoriums used for both speech and music. From his curves the period of reverberation in satisfactory concert halls is about 25 per cent. greater than the period in halls of the same size which are required for speech as well as music. Fig. 43 has

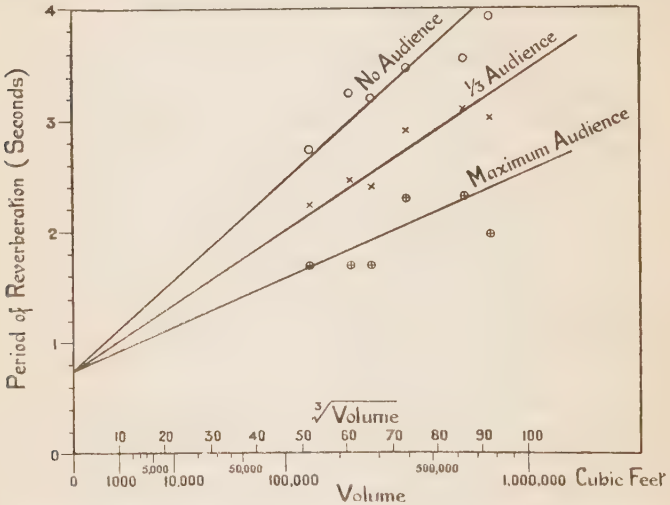

Period of Reverberation (Seconds)
No Audience
⅓ Audience
Maximum Audience
∛Volume
10 20 30 40 50 60 70 80 90 100
0 1000 5,000 10,000 50,000 100,000 500,000 1,000,000 Cubic Feet
Volume

Fig. 43.—Relation between volume of hall and the preferred reverberation period for music (Watson).

been drawn from the curves given by Watson for various sizes of audiences in concert halls used for music alone. The volumes are plotted upon a cube-root scale since, as we have seen on p. 69, the reverberation periods of halls tend to be proportional to the linear dimensions. The data of Fig. 43 are included in Table IV.

Fig. 44 shows three curves relating to halls with maximum audience. The observation points refer to the various halls enumerated in Table III and Table IV. One of the curves given is that derived

by Watson for speech and music.* The figure also shows the curve from Fig. 43 derived by Watson for music alone, and the curve given by Lifshitz to cover all classes of auditoriums whether for music or speech.

TABLE IV.—REVERBERATION IN VARIOUS HALLS

Building.	Volume.	Seating capacity.	Reverberation.		Remarks.
			Empty.	Full.	
	Cu. ft.	Persons.	Secs.	Secs.	
New England Conservatory of Music	4,100	..	⅛ full = 1·1		Music.
Royal Institution (London)	46,000	700	1·2	0·7	Speech.
Little Theatre (New York)	59,000	..	2·1	1·26	..
Wesley Auditorium, University of Illinois	101,000	500	2·45	1·2	..
Macon Church	111,000	..	2·4	1·3	..
House of Commons	127,000	570	3·3 †	1·45†	Speech.
Kilburn Hall, Eastman School of Music, Rochester, N.Y.	140,000	510	2·7	1·65	Music.
Smith Concert Hall, University of Illinois	231,000	1050	3·25	1·7	,,
Detroit Orchestral Hall	360,000	..	3·8	1·55	,,
Leipzig Gewandhaus	400,000	1500	3·6	2·3	,,
Auditorium, University of Illinois	425,000	2150	4·3	1·4	..
Boston Concert Hall	650,000	2400	3·6	2·3	Music.
Eastman Theatre, Rochester, N.Y.	790,000	3340	4·0	2·08	,,
Great Hall, College of New York	820,000	..	3·8	2·0	..
Munic. Pier Auditorium	1,100,000	..	3·9	2·15	..

Values for maximum audiences, derived from the smooth curves of Fig. 44, are given in Table V. The curves themselves express only average results, and the values given in the table must be interpreted

* Watson, *Acoustics of Buildings*, p. 32, 1932.

† Computed values.

in this light. Auditoriums are known the reverberations of which deviate from those in the table by several tenths of a second in either direction, and yet are regarded as of fairly satisfactory quality. As regards music, something will depend on its character. Excess of reverberation will impart an

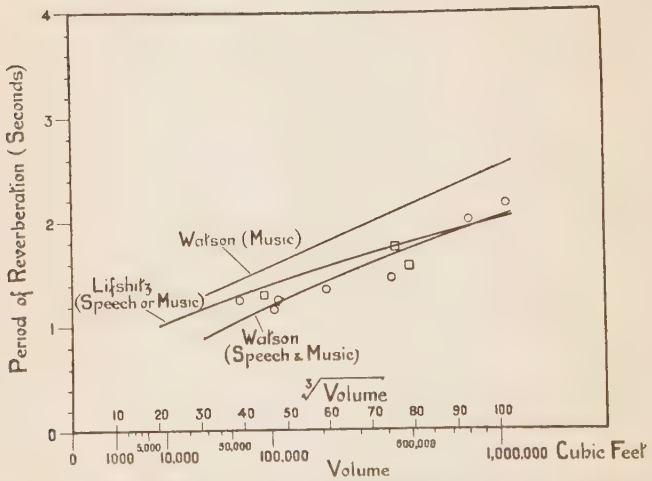


FIG. 44.—Relation between volume of hall with maximum audience, and the preferred reverberation periods for speech and music.

increased sonority which may add greatly to the impressiveness of slow stately music, but will blur the vividness of lively and rapid passages.

Owing to the fact that the absorbing powers of materials usually depend somewhat upon the pitch of the note concerned, the period of reverberation of a hall will show a like dependence. The different effects on the sounds from the various instruments of an orchestra resulting from changes in the absorbing power of a hall (*e.g.* from varying sizes of audience) would doubtless be revealed to a trained musical ear by the change in the balance of tone from the

orchestra. In view, however, of the imperfections of the normal ear, referred to on p. 33, it is unlikely that the effects of moderate variations in the absorbing power (and consequently in the reverberation period) are important.

TABLE V.—RELATION BETWEEN VOLUME OF HALL AND PREFERRED REVERBERATION FOR MAXIMUM AUDIENCE

Volume of hall.	Speech and music.		Music. Watson.
	Lifshitz.	Watson.	
Cu. ft.	Secs.	Secs.	Secs.
20,000	1·1	0·8	1·2
50,000	1·3	1·0	1·4
100,000	1·4	1·2	1·6
200,000	1·6	1·4	1·8
500,000	1·8	1·7	2·1
1,000,000	2·0	2·0	2·5

Reverberation Tolerance.

The question arises as to the extent to which deviations from the optimum reverberation condition can be tolerated. Naturally, this is even more difficult to assess than the optimum condition itself. In view of the concensus of taste indicated above, it is probable, however, that appreciable deviations from the optimum conditions would be found objectionable and would put a strain upon the patience of the hearer.

W. C. Sabine, speaking of the large lecture room of the Jefferson Physical Laboratory having a volume of 50,000 cu. ft., regarded its condition empty, with a period of 4 seconds, as entirely impracticable for speaking purposes, but when it was

full of people the period was 1·8 seconds, and this he considered to be fairly satisfactory.* He did not, however, regard such a period with complete approval. He rejected, for instance, a first design of the Little Theatre in New York, having a volume somewhat greater than 60,000 cu. ft., although over the frequency range 256(c^{i}) to 4096(c^{v}) it yielded a period of reverberation of 2·2 seconds—a state comparable with that of many theatres of which the acoustics are not normally questioned. Sabine, however, sought exceptional quality in this case and, passing over as inadequate a modification yielding 1·8 seconds, finally approved a design in which for musical notes over the range 256(c^{i}) to 2048(c^{iv}), the period for a maximum audience lay between 1·1 and 1·5 seconds.†

Experiments have been carried out by V. O. Knudsen ‡ on the effect of reverberation upon the quality of speech. Articulation tests were conducted in which a large number of disconnected words were read in turn in the auditorium, and an observer wrote down his interpretation of the sounds heard. The percentage of correct interpretations, usually called the "percentage articulation," was determined. Such articulation tests form a standard procedure in telephone work, and suitable lists of words have accordingly been compiled which give a suitable variety of consonantal and vowel sounds. Knudsen's measurements were made in several auditoriums having approximately the same volumes and shapes, but different times of reverberation.

* W. C. Sabine, *Collected Papers on Acoustics*, p. 105, 1922.
† *Loc. cit.*, p. 174.
‡ Knudsen, *Phys. Rev.*, **22**, 206, 1923.

The results given below are the average of observations taken in different parts of the auditoriums.

Table VI.—Percentage Articulations (Knudsen)

Volume.	Reverberation.	Word articulation.	Vowel articulation.	Consonant articulation.
Ft.^{3}	Secs.	Per cent.	Per cent.	Per cent.
320,000	7·5	44·0	88·0	65·4
280,000	5·3	56·3	92·0	73·0
310,000	5·0	64·5	97·0	79·0
280,000	3·0	82·2	99·8	88·5
270,000	2·8	84·8	99·6	91·7

Knudsen also conducted tests in a small room having a volume of about 4000 cu. ft., the reverberation in which was controlled by bringing in different amounts of hair felt. The results showed that, as the time of reverberation was reduced from 5 seconds to 0·6 second, the word, vowel, and consonant articulations increased, almost uniformly, from 51, 94, and 71 per cent. to 92, 99, and 96·5 per cent. respectively.

Unfortunately, Knudsen's work in the large halls does not extend into the region 1 to 2 seconds where the reverberant condition is usually regarded as satisfactory. Telephone engineers regard an articulation of 70 per cent. as the limit of commercial telephone speech, so we may conclude from the table that a period of 4 seconds upwards would be impracticable for a large hall, a conclusion that agrees with Sabine's views. Even a word articulation of 84·8 per cent. associated with the lowest period of 2·8 seconds would represent in practice a very wearying condition for a hearer.

CHAPTER V

THE MEASUREMENT OF ABSORPTION COEFFICIENTS

We have seen that, for a room to attain its optimum reverberant condition, it is necessary to arrange that the various exposed surfaces possess in the aggregate the requisite absorbing power. We thus require to know the absorption coefficient or the absorbing power of unit area of each material present.

Various methods have been suggested for measuring this coefficient of absorption for building materials and surfacings. As has been indicated, one method is to make reverberation measurements in calibrated test chambers. In other methods which have been employed, sound is directed towards a test specimen, and the proportion of the incident sound which undergoes reflection is measured.

The Sabine Reverberation Method

The general manner in which the duration of reverberation in a room depends upon the total absorbing power of the surfaces has already been referred to (p. 68), and it has been indicated how the absorbing power of introduced absorbents may be calculated from the change in the period of reverberation.

Rate of Decay of Sound in a Room.

First of all, then, it is necessary to determine the duration of audibility in the empty room for various initial intensities of the source. Sabine * used different combinations of identical organ pipes placed so far apart in the room that it could be assumed that they did not react on each other, and that the total power of any combination was the sum of the powers of the separate pipes. The ratio of intensities conveniently available by such means—Sabine normally used from one to four organ pipes in different tests—is, however, small compared with the ratio of the standard initial intensity of the sound to the minimum necessary for audibility, which ratio, as we have already noted, is taken as one million times.

In determining the rate of decay of sound in a room, note is made of the duration of audibility, t_1, when a certain source is used, and of the duration, t_n, when a source of the same frequency but having n times the intensity is employed. Since the intensity decays to the same limit of audibility in each case, it follows from (4) on p. 67 that an exponential relation should be obtained of the form

$$\log_e n = A(t_n - t_1) \quad . \quad . \quad (8)$$

where A, defined by Sabine as the rate of decay of sound in the room, has the value $vaS/4V$ according to Jaeger's theory.

If Jaeger's theory is accepted and the velocity of sound v and the volume V of the room are known, this experiment gives the total absorbing power aS of

* W. C. Sabine, *Collected Papers on Acoustics*, p. 1, 1922.

the surfaces of the room. Provided the absorbing power of the room is independent of the intensity of the sound concerned, and provided also that the threshold sensitivity of the ear is not appreciably affected either by fatigue or by the initial intensity of the sound, it follows that a straight-line relation should be obtained between $\log n$ and t_n. Over a seven-fold range of intensity Sabine found such a relation to hold. In reverberation experiments at the National Physical Laboratory, Davis and Fleming,* using an electrodynamic loud-speaker (p. 12) in a reverberant room have found that the linear relation still holds over a fifteen-thousand-fold range of intensity. It seems possible, however, that in a room in which the decay of sound was very rapid, fatigue of the ear would cause appreciable departure from the simple law.

Open-window Method of Determining the Absorbing Power of a Room.

An alternative reverberation method employed by Sabine to ascertain the absorbing power (aS) of a room is to measure it in terms of that of an open window. If aS and $(aS+w)$ are respectively the total absorbing powers of the room with the window closed and open, and if t_1 and t_w are the respective durations of audibility, then (a) if the initial intensity of sound is the same in the two cases

$$(t_1/t_w - 1) = w/aS \quad . \quad . \quad . \quad (9)$$

(b) if the source has the same activity E in the two cases, the relation (4) yields

$$\frac{4E}{vaS} e^{-\frac{vaSt_1}{4V}} = I_{\min} = \frac{4E}{v(aS+w)} e^{-\frac{v(aS+w)t_w}{4V}} \quad . \quad (10)$$

* Davis and Fleming, *Phil. Mag.*, **2**, 51, 1926.

whence

$$\log_e(1+w/aS)=(v/4V)[aS(t_1-t_w)-wt_w] \quad . \quad (11)$$

from which (aS) may be determined.

Absorbing Power of Introduced Objects.

The absorbing power of objects introduced into a room can be determined by conducting reverberation measurements for two strengths of source both with and without the objects in the room. This gives the rate of decay of sound and thus the absorbing power in the two cases. By difference the absorbing power of the introduced objects is deduced.

The method actually adopted by Sabine was essentially a substitution method, and expressed the absorbing power of the objects in terms of an equivalent area of open window. The duration of audibility was noticed in the empty room both with the window closed (t_1) and open (t_w), and also with the absorbent introduced (t_x).

For standard conditions of initial intensity we then have

$$\frac{t_1}{t_w}-1=\frac{w}{aS}; \qquad \frac{t_1}{t_x}-1=\frac{X}{aS} \quad . \quad . \quad (12)$$

whence

$$\frac{X}{w}=\frac{\frac{t_1}{t_x}-1}{\frac{t_1}{t_w}-1} \quad . \quad . \quad . \quad (13)$$

If the standard initial intensity is not attained in each case, but the activity of the source is maintained constant, the general relations become more complicated, and equations of the form (11) are involved. In actual experiments with a single source, the

initial intensity in the room will be affected by the presence of an absorbent, though for some purposes the effect may be neglected.

Coefficient of Absorption.

We have seen that Sabine found the total absorbing power of a material, or of an open window, to be proportional to the area exposed. In the case of many absorbing materials it is therefore convenient to express experimental results in the form of the absorbing power per unit area of exposed surface. As already remarked, this quantity is called the coefficient of absorption of the material under the conditions of the test.

We may, however, recall the fact that, on the ordinary hydrodynamical theory of sound, when an aperture is small compared with the wave-length of the sound received it does not transmit the same amount of sound as that crossing an equal area of the wave front of the primary waves. For a circular aperture about 82 per cent. is transmitted; for a long narrow slit, the breadth of which is small compared with the wave-length, the energy transmitted may even considerably exceed that corresponding to an equal area of the primary waves.*

Similarly, P. E. Sabine,† working under the improved conditions afforded by the Sabine Laboratory (p. 182), has found that when the dimensions of a highly absorbent sample are not great compared with the wave-length of the sound, then the apparent absorbing power per unit area is a function of the area of the sample, of its shape, and also of its loca-

* Lamb, *Dynamical Theory of Sound*, 2nd edit., p. 250, 1925.

† P. E. Sabine, *Phys. Rev.*, **19,** 402, 1922.

tion relative to other absorbing surfaces. For example, in one series of tests, measurements were made with areas ranging from 0·14 to 10·0 square metres. For felt, at the frequency (1024) for which its absorption was a maximum, the absorbing power per unit area decreased with increasing area, the ratio in extreme cases being about 3 to 1. At other frequencies the variations were not so great. As regards the shape of the test specimen, it was found that in the case of felt of an area of 3·3 square metres and a frequency of 1024 long narrow shapes showed an absorbing power 50 per cent. greater than an equal area in the form of a square.

These results suggest some qualification in the definition of sound-absorption coefficients. They should be expressed for areas sufficiently great for the result to be independent of area. It appears desirable in comparing materials to use samples of the same standard size and shape, say, 10 ft. square. This aspect of the work would doubtless warrant further investigation.

General Discussion of Reverberation Method.

It will be profitable to examine more closely the experimental basis of the reverberation tests referred to above. The gist of the theory is contained in the facts that the duration of audibility of residual sound is found to be practically independent of the positions of the source and of the observer, and that the efficiency of an absorbent is independent of its position in the room.

It is accordingly necessary to verify by experiment that these conditions are satisfied in any room in which reverberation tests are carried out.

It may be noted that reverberant sound dies away in a fluctuating manner owing to the rapid shifting of the interference system in the room after the source ceases. Sabine's experiments show, however, that these fluctuations have little importance when one is estimating the decay of sound by ear. Another practical point is that, although the source may be sounding in a steady state, the ear, depending on its position in the room, may be subjected either to the loudness of a partial node or the feebleness of an antinode. Again, Sabine's experiments go to show that, at any rate for reverberant rooms in which the sound decays moderately slowly, the threshold sensitivity of the ear is not appreciably affected by such differences in initial excitation.

The theory of reverberation work postulates uniform mixing of sound energy throughout the room as regards both position and direction. If, however, a large area of one of the surfaces is markedly more absorbent than the rest, the uniformity of distribution may be impaired. Large test-rooms are thus desirable, for while the total surface of the room should be large compared with that of a test sample, we have already seen that the samples themselves must not be small compared with the wave-length of the sound concerned.

It should further be noted that the vibrations of the air in the room may react on the output of the source. For example, the proximity of objects to the source may appreciably affect the output; Sabine quotes a case where the output of a source was considerably increased by an alteration of the interference system in the room caused by introducing an absorbent. The proximity of other sources may

also affect the output. Such reactions upon the source would be specially pronounced when the frequency of the source approximates to one of the resonant frequencies of the air of the room or of one of the walls, etc.

To recapitulate,* it is desirable to avoid resonant frequencies, to use a single source, and in each position to vary its output in a known manner, so that reaction effects may be eliminated. The source should be of a type which is affected as little as possible by reaction effects. Large reflectors slowly rotating in the room may be employed to average out errors (see p. 184), whether due to lack of uniformity of sound within the room or to reaction upon the source, or to any effect the interference fluctuations may have on the ear during the decay of the sound. Further, by conducting the experiments with at least two different intensities of initial sound, the characteristics of the ear may be largely eliminated.

Stationary-wave Method

A method of measuring, on a small scale, the absorbing power of small samples of materials was first suggested by Tuma,† and was subsequently employed in experimental work by Weisbach ‡ and later by H. O. Taylor.§ In this the test specimen, in the form of a flat sheet, closes one end of a cylindrical tube. The other end is open and faces a source of sound of constant pitch and intensity.

* See Davis, *Phil. Mag.*, **2,** 543, 1926.
† Tuma, *Wien. Ber.*, **111,** 402, 1902.
‡ Weisbach, *Ann. d. Phys.*, **33,** 763, 1910.
§ Taylor, *Phys. Rev.*, **2,** 270, 1913.

Sound-waves from the source pass through the tube and are reflected back by the specimen. When the latter is a perfect reflector the amplitudes of the entrant and reflected waves are equal, and through their interference the usual system of stationary waves is formed inside the tube. At some points—loops—along the length of the tube there is no pressure variation, but at others—nodes—the variation is a maximum. If the specimen is an imperfect reflector the amplitude of the reflected wave is less than that of the incident wave; consequently, there are no positions where the reflected wave exactly neutralises the incident wave, but only a series of maxima and minima.

If the pressure amplitudes of the incident and reflected waves be i and r respectively, then at each of the nodes the amplitude N is equal to $(i+r)$, whilst at the antinodes its value A is equal to $(i—r)$. If the ratio N/A of the amplitudes at the nodes and antinodes is measured, the relation between the incident and reflected amplitudes is readily calculable since

$$r/i=(A—N)/(A+N).$$

Now the sound energy in the incident wave is proportional to i^2, and that in the reflected sound to r^2. The fraction of the incident sound energy lost at reflection—that is, the coefficient of absorption, a, of the material—is thus equal to $(i^2—r^2)/i^2$. The formula is

$$a=\frac{(i^2—r^2)}{i^2}=\frac{4}{2+A/N+N/A}.$$

In practice, repeated reflections take place at the open end of the pipe, but this does not invalidate

the simple theory given, for in the steady state the total effect can be represented by two simple trains of waves, one incident and the other reflected.

Weisbach * used in his experiments a wooden pipe 238 cm. long and 25 cm. in diameter, with walls 4 cm. thick. The length of the tube was adjustable by means of a metal extension, so that the tube could be tuned to the particular note emitted by the source. The test specimen was mounted at one end of the tube, and was backed by a piece of marble 2·5 cm. thick to prevent transmission. The source was an electrically driven tuning-fork mounted upon a resonance box some 10 to 30 cm. outside the open end of the tube. Steadiness of amplitude of the source was ensured by observing the amplitude of the prongs of the tuning-fork through a microscope. The pressure variation due to the sound within the tube was explored by means of an electromagnetic microphone mounted upon a long wooden slider which projected through the open end of the tube, and by means of which the position of the telephone in the tube could be conveniently controlled and measured. The response of the telephone in the various positions along the tube was measured by means of a string galvanometer.

Weisbach's results were expressed in a form which differs somewhat from the absorption coefficient as defined on p. 94. Moreover, to allow for the fact that he did not obtain very perfect nodes when using an approximately perfect reflector, Weisbach introduced a somewhat arbitrary correction factor in calculating his results. In view of the difficulty of now bringing the values into uniformity with the accepted

* Weisbach, *loc. cit.*

definition, Weisbach's results are not included in the tables of absorption coefficients given later.

Taylor * used a wooden experimental pipe 115 cm. long, having a square section measuring 9 cm. × 9 cm. As a source of sound he employed a stopped organ pipe, the note of which was purified by means of a series of filters consisting of a number of resonators arranged at the open end of the experimental pipe, each resonator being designed to eliminate one of the harmonics emitted by the organ pipe. This use of branch pipes as acoustical filters is due to Quincke (p. 8). To measure the sound amplitudes within the experimental pipe a Rayleigh disc instrument was employed. The variations of intensity within the pipe were explored, and the curve connecting intensity with distance along the pipe was found to be of simple sine-wave form, so that, as far as this evidence went, Taylor was using a pure tone. Owing to the presence of the delicate suspension fibre the Rayleigh disc instrument could not be moved, and it was necessary to move the whole of the rest of the apparatus, a somewhat cumbersome proceeding.

Taylor's apparatus is illustrated in Fig. 45. A glass tube communicating with the Rayleigh disc projected into the experimental pipe. In taking observations, the pipe, together with the attached organ pipe, was moved along a graduated scale in centimetre steps. Observations of intensity were made at each step, and finally the maxima and minima of intensity were exactly located and measured. From the values of A^2 and N^2 thus determined, the coefficient of absorption of sound for the

* Taylor, *loc. cit.*

test material closing the end of the pipe was calculated as above. The results are given on p. 118.

Paris,* at the Signals Experimental Establishment, Woolwich, has carried out some experiments, by the stationary-wave method, on the absorbing power of certain acoustical plasters (p. 118). The general arrangement is clear from the section in Fig. 46. The experimental pipe, 12 in. in diameter and 5 ft. long, consisted of two drain-pipes cemented

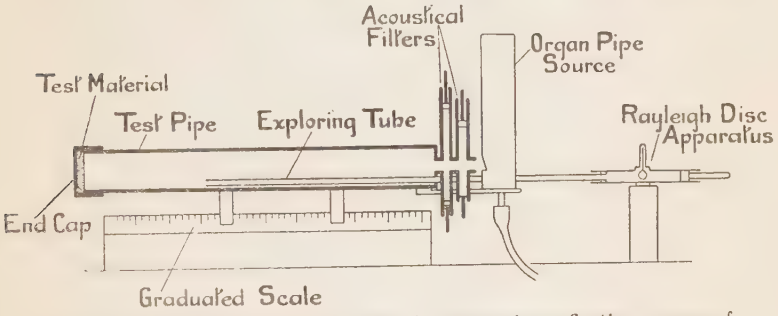


FIG. 45.—Stationary-wave apparatus for measuring reflecting powers of materials (Taylor).

together. To minimise the communication of extraneous vibrations to the contained air, the experimental pipe was mounted inside a felt-lined wooden box supported on four legs set in concrete, and was further insulated from its supports by pieces of felt. One end of the pipe and its housing passed through the wall to the outside of the laboratory, as shown in Fig. 47, Plate XIII. The source of sound was a loud-speaker actuated by a valve oscillator. The open end of the pipe and the source were completely enclosed in a sound chamber to protect the source from varying reactions that might arise by the movement of an observer in the laboratory.

* See Paris, *Proc. Phys. Soc.*, 1927.

The test plasters were mounted within a wooden ring 1 in. thick, screwed to a 5-ply wooden disc which served as a backing to the plaster (see Fig. 48, Plate XIII). Any crevices between the specimen and the wooden ring were filled in with a mixture of plaster of Paris and water-glass, which was allowed to set hard before the specimen was tested. When

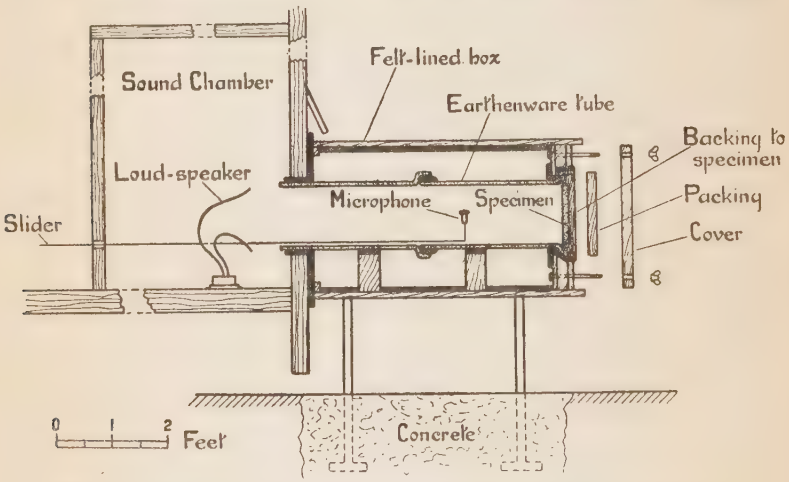


FIG. 46.—Stationary-wave apparatus for measuring reflecting powers of materials (Paris).

fixing the specimen in place for a test, a washer of "basil" cloth or $\frac{1}{8}$-inch rubber was placed between the end of the tube and the ring of the mounting to ensure an air-tight fit.

For the intensity measurements, a hot-wire microphone (p. 18) was employed. This was carried at the end of a long wooden slider, the orifice of the microphone being as nearly as possible on the axis of the tube. If the resonant microphone is sufficiently large in comparison with the diameter of the test-pipe, reaction due to the presence of the micro-

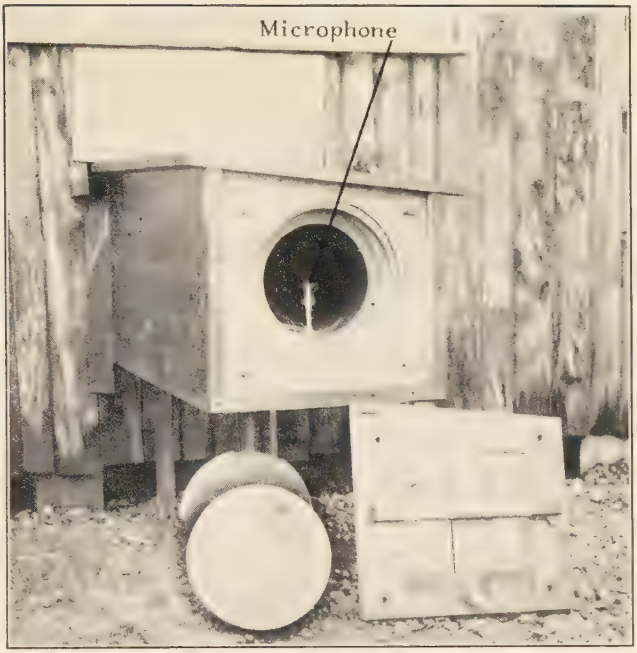


FIG. 47.—View of Paris's stationary wave apparatus from outside of laboratory. See p. 101.

FIG. 48. -Specimen of an acoustic plaster (Paris). See pp. 102, 156.

[*To face page* 102.

phone will be experienced. The microphone and tube will, in effect, combine to form a double resonator of the Boys type, and the effect of sliding the microphone along the tube will simply be to vary the coupling between the two components. Paris has investigated this double-resonator effect, and finds that the observed absorption coefficient should be increased by about 5 per cent. in consequence. Some of Paris's results are given in Table X, p. 118.

In a stationary-wave apparatus at the National Physical Laboratory,* a loud-speaker actuated by audio-frequency current of pure wave-form is used as a source of sound. The pressure at various points along the experimental pipe is measured by an electrodynamic microphone, the small electromotive forces at the terminals being determined by the substitution method described previously (p. 24). As a variation, in case the presence of the microphone should interfere with the distribution of sound in the pipe, a long tube is used to convey the sound from the point under study to the microphone. This procedure, however, has but little effect on the results. To avoid any interference with the output of the source or with the sound entering the pipe, the apparatus is set up in a special room and all measurements of intensity are taken from outside. The pipe is placed with its open end facing an open window of an upper floor, and the loud-speaker is suitably suspended outside the window and facing the pipe. In later experiments, the loud-speaker is mounted within an enclosure at the end of the pipe. Some results are given in Table X, p. 118.

* *Nat. Phys. Lab. Ann. Rep.*, p. 67, 1924.

The stationary-wave method is also in use at the Bureau of Standards, Washington.* The arrangement adopted is essentially similar to Taylor's. The sound is conveyed to a vertical test-pipe by means of a tube fitted with a series of acoustical filters, and sound intensities within the pipe are explored by means of a long tube connected externally to a sound measuring instrument. The source is a loudspeaker, and an electrical microphone is employed for sound measurement. A different pipe is used for each frequency, its length being chosen to give resonance in each case. In practice the various maxima were found to vary in intensity along the length of the pipe, presumably owing to absorption at the walls. The minima are similarly affected. To allow for this it is assumed that the amplitude of a wave decreases exponentially with the distance traversed. The absorption coefficient (a) is then given by the modified formula

$$a=1-\left[\frac{N_1-A_1+\frac{A_2-A_1}{2}}{N_1+A_1-\frac{A_2-A_1}{2}}\right]^2$$

where N_1 is the amplitude of the maximum nearest the absorbing substance, and A_1, N_2, A_2 are successive maxima and minima. A selection of results is given in Table XI, p. 119.

Watson's Method

Another method of measuring the sound reflected from a material has been devised by Watson.†

* *Bureau of Standards Scientific Paper*, No. 526, 1926.

† Watson, *Bull. No.* 127 *of the Univ. of Illinois Engineering Experiment Station*, 1922.

In this method, measurements are made of the sound transmitted and reflected by a partition clamped over an aperture between two adjacent rooms. Fig. 49, Plate XIV, shows the general disposition of apparatus used in the reflection measurements. An organ pipe at the focus of the parabolic reflector seen to the left of the doorway was used as a source of sound. Sound emerging from the reflector passed to the doorway where it was reflected by the test sample to the measuring instrument—a Rayleigh disc and resonator shown on the iron tripod in the centre. The deflections of the instrument were observed through a small glass window from the booth shown on the right. This booth was provided to eliminate the disturbing effect of the observer, who must necessarily have some freedom of motion which would alter the distribution of sound in the room.

It is evident that a number of complications will occur with this apparatus. Measurements of the reflected sound will be affected by the stray sound in the room which will influence the Rayleigh instrument even when no reflecting material is used. There will, moreover, be a complicated pattern of interference phenomena in the room due to repeated reflections of sound from the walls. Nevertheless, Watson obtained consistent and rational results. Full details of his procedure do not appear to be available, but he assumed an open doorway to transmit 100 per cent. of the incident sound and to reflect none: he also assumed that a hard board reflected 100 per cent. See pp. 120, 179, 197.

The Watson method is receiving attention at the National Physical Laboratory. To reduce stray

sound in the reflection room, the region in which reflection measurements are made is screened somewhat from the source by means of a suitably placed partition. All exposed surfaces of the walls, floor, and ceiling are heavily lagged with sound-absorbing felt or mattresses, so that reflections from these surfaces are largely suppressed and interference phenomena are minimised. The electrical equipment already described (p. 24) is used to produce and measure the sound, so that all measurements may be made from a distance and the disturbing effect of the observer is eliminated. The equipment is particularly suitable for the purpose, as the pitch of the sound used can be altered without fitting a fresh source (as is not the case when an organ pipe is used), and further the same microphone may be used throughout the measurements whereas in the case of a Rayleigh disc resonator, a different instrument is necessary each time the pitch is changed. The N.P.L. apparatus will be described in greater detail later when transmission measurements are discussed (p. 198).

One or two points should be noticed in connection with the Watson method. In the first place, the panels may vibrate as a diaphragm under the influence of the sound: Watson observed such behaviour when thin plaster partitions were used. The normal reflection from the material will thus be complicated by the acoustical consequences of this vibration. The extent of such vibration will depend upon the size and clamping of the "diaphragm," and will be greatest at the frequency of resonance. It is thus desirable for proper appreciation of results that reflection should be studied both for the free

Fig. 49.—Apparatus used by Watson in measurements of sound reflection and transmission. See p. 105.

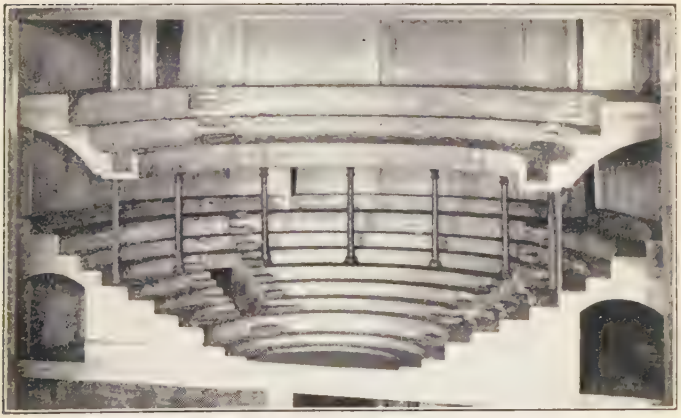


Fig. 55.—Photograph of interior of wooden model of Royal Institution Lecture Theatre. See p. 131.

[*To face page* 106

partition and for a case in which vibration is restricted. Also, in general, partitions should be of the size in which they will be used in practice. Clearly also the "beam" of sound should be large enough to cover the whole test partition. A second

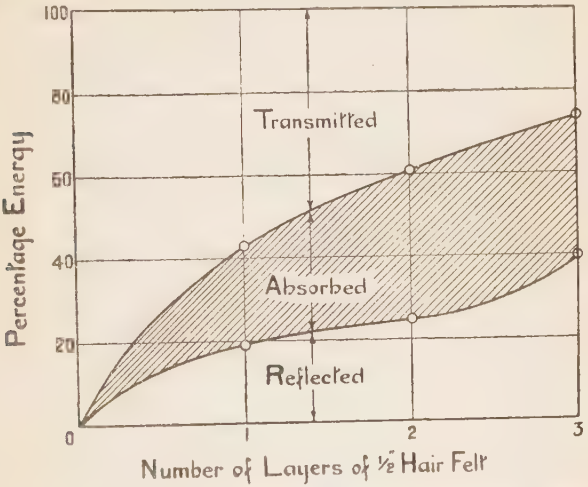


Fig. 50.—Transmission and reflection of sound by hair felt (Watson).

general point in connection with the method is that the angle of incidence of the sound upon the reflector is fixed. In practice, sound usually falls upon a partition more or less equally from all directions. It is desirable therefore in using the Watson method to be able to vary the disposition of the apparatus so that the effect of different angles of incidence on the absorption coefficient may be studied.

Fig. 50 shows graphically the reflection and transmission by layers of half-inch hair-felt. Fig. 51 presents similar results for a series of vibrating partitions.

Kennelley's Method

Kennelley * has recently indicated a novel method which deals with small samples and normal incidence. When an ordinary telephone receiver is actuated by alternating current, the intensity of the sound emitted depends upon the condition of the air in its

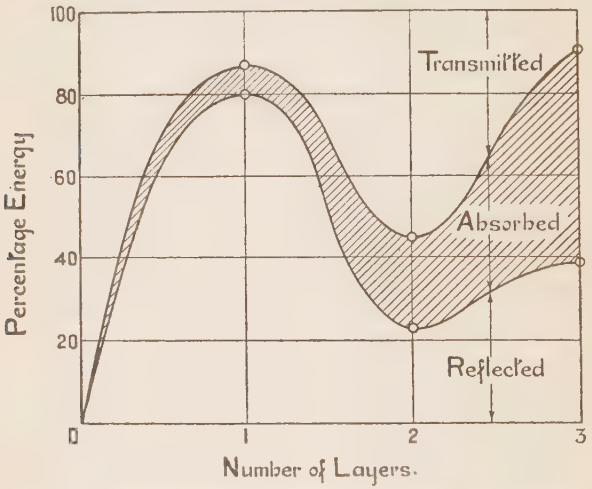


Fig. 51.—Transmission and reflection of sound by vibrating partitions (Watson).

vicinity. If the receiver is close to and facing a wall, the emission differs from that which would obtain in free air. The resistance of the air to the motion of the diaphragm is in fact affected by the reflected sound. This change of resistance may be detected by the changed behaviour of the receiver in relation to the applied electrical current. Thus, from measurements of the electrical characteristics of the receiver when facing different materials, the reflecting power of the materials may be deduced.

* Kennelley, *Frank. Inst. Journ.*, **200,** 467, 1925.

General Remarks

It is clear that the methods set out above for determining absorption coefficients do not necessarily measure the same quantity. In the stationary-wave method small specimens and normal incidence are employed and the reflecting power of backed materials is measured under conditions where diaphragm-like vibration is reduced to a minimum. The Sabine method measures the reflecting power of large areas, when subjected to incidence from all directions—the most usual case in practice. The size and method of fixing of the specimens can be arranged to approximate to those in actual use. The Watson method utilises oblique incidence and panels of moderate size, with or without backing. It is evident that each of the various methods presents problems of its own, and that further work is necessary on the whole question.

Tables of Absorption Coefficients

The tables given below (pp. 112–121) present absorption coefficients for a number of materials as measured by various observers. The figures do not specify the intensity of the sound concerned, and indeed it appears to be true that for ordinary conditions the dependence, if any, of the absorbing power upon sound intensity is not marked.

As already noted (p. 63), Rayleigh has shown that the degree of absorption of a rigid porous wall depends upon the pitch of the test note. The absorbing power of non-rigid materials, such as wooden panelling, should moreover show a depend-

ence upon pitch for another reason. The materials vibrate as a whole, and, owing to resonance, they should exhibit selective absorption for sounds of certain frequencies. It is consequently necessary to study absorbing powers over a wide range of musical pitch.

Tables VII and VIII contain results which have been compiled from reverberation data and curves in W. C. Sabine's various published papers. They reveal a number of interesting points which may be mentioned briefly. Starting with the test note of lowest pitch, the absorbents in general show increasing absorbing power as the pitch of the test note is raised, and many of them exhibit a maximum value towards the upper part of the range of frequencies considered.

The values for absorption by a brick wall show a steady increase with frequency. According to the theory set out by Rayleigh it appears that, if reasonable values are adopted for the variables concerned, the absorption in such a case should be approximately proportional to the square root of the frequency of the sound (p. 64). Actually, when plotted, Sabine's results show a linear relation between sound absorption and the square root of the frequency, though the line does not pass accurately through the origin.

With reference to the absorbing power of persons in an audience it will be seen that they are more absorbent for high notes than for low, so that low notes are purified in consequence. For the region important for distinct speech (256 to 4096) the absorbing power is, however, substantially uniform. Figures for an audience are expressed in two forms

(Tables VII and VIII); one gives he coefficient of absorption of floor space covered by an audience as ordinarily seated, and the other gives the total absorbing power of each individual of the audience so seated. The two sets of figures agree on the assumption that each member of a seated audience occupies about 5 sq. ft. of floor space. Figures for seat cushions are also given in two forms (Tables VII and VIII); they are consistent if a seat cushion has an exposed area of $2\frac{3}{4}$ sq. ft.

As regards the absorbing power of felt, it will be noted that the absorbing power reaches a maximum for some frequency intermediate between the highest and lowest tested. Sabine infers that absorption occurs partly by penetration of sound into the pores of the felt and partly by a yielding of the mass as a whole, resonance in the latter process being revealed by the fact that the maximum shifts to a lower pitch, as the thickness of felt is increased. The absorbing efficiency of a felt would thus depend upon the flexibility and viscosity of the mass as a whole, and on its porosity. It would not be largely dependent upon the nature of the material employed, except in so far as the nature determines the closeness and other characteristics of the felting process. In giving the figures for the various kinds of felt, Sabine remarks that information as to the ratio of solid material to free space does not fully define a felt, for the absorbing power depends upon the size of the pores and upon the other properties mentioned above.

Ordinary wool- or hair-felts are liable to rapid deterioration by moths. Sabine found a jute-felt to be sufficiently durable to be suitable for acoustical

TABLE VII.—VARIATION OF ABSORPTION COEFFICIENTS WITH FREQUENCY

(W. C. Sabine: reverberation method)

Material.	Absorption coefficients for frequency						
	64.	128.	256.	512.	1024.	2048.	4096.
Open window	*1·00*	*1·00*	*1·00*	*1·00*	*1·00*	*1·00*	*1·00*
Audience, as ordinarily seated	0·35	0·72	0·89	0·95	0·99	1·0	1·0
Brick wall, 18 in. thick—unpainted	0·021	0·024	0·025	0·031	0·042	0·049	0·07
painted	0·011	0·012	0·013	0·017	0·02	0·023	0·025
Wood sheathing (pine, 2 cm. thick)	0·064	0·098	0·11	0·10	0·081	0·082	0·11
Cushions							
Elastic cotton, under canvas and short nap plush	0·37	0·61	0·62	0·76	0·91	0·73	0·47
Hair, under canvas and leatherette	0·25	0·42	0·47	0·72	0·47	0·27	0·16
Long hair, under canvas and plush	0·31	0·36	0·41	0·67	0·62	0·51	0·34
Vegetable fibre, under canvas and cloth	0·23	0·28	0·39	0·54	0·59	0·53	0·45
Felts							
Asbestos, ¾ in. thick, 33 per cent. volume is solid material	0·06	0·06	0·14	0·32	0·25	0·19	0·18
Do. felted to asbestos cloth	0·07	0·08	0·17	0·35	0·30	0·23	0·20
Hair and asbestos, 19 per cent. volume is solid material	0·04	0·05	0·11	0·38	0·55	0·46	0·39
Hair-felt, 12 per cent. volume is solid material	0·09	0·10	0·20	0·52	0·71	0·66	0·44
Do. covered with burlap attached with silicate of soda	0·13	0·13	0·33	0·74	0·76	0·49	0·18

TABLE VII.—VARIATION OF ABSORPTION COEFFICIENTS WITH FREQUENCY—*continued*

(W. C. Sabine: reverberation method)

Material.	Absorption coefficients for frequency						
	64.	128.	256.	512.	1024.	2048.	4096.
Hair-felt, with membrane (0·87 oz. per sq. ft.) stretched near surface	0·17	0·20	0·40	0·65	0·27	0·14	0·11
Do. with membrane (2·58 oz. per sq. ft.) stretched near surface	0·25	0·29	0·41	0·32	0·19	0·11	0·08
Do. 2 in. from wall	0·10	0·11	0·26	0·62	0·73	0·66	0·45
Do. 4 „ „	0·11	0·13	0·30	0·66	0·74	0·66	0·45
Do. 6 „ „	0·12	0·15	0·35	0·68	0·75	0·66	0·45
Do. at centre of room with barrel ceiling	0·14	0·15	0·32	0·96	1·27	1·02	0·62
Do. at sides of room with barrel ceiling	0·11	0·20	0·25	0·54	0·43	0·48	0·20
Jute-felt, ½ in. thick	0·038	0·049	0·076	0·17	0·48	0·52	0·51
Do. 1 in. „	0·12	0·15	0·22	0·54	0·63	0·57	0·52
Do. 1½ in. „	0·19	0·24	0·38	0·63	0·65	0·57	0·52
Do. 2 in. „	0·27	0·34	0·50	0·69	0·67	0·58	0·52
Do. 2½ in. „	0·34	0·43	0·59	0·75	0·67	0·58	0·52
Do. 3 in. „	0·40	0·50	0·66	0·77	0·68	0·58	0·52
Membranes							
0·87 oz. per square foot.	0·01	0·01	0·04	0·1	0·07	0·02	0·01
2·58 „ „ „	0·05	0·06	0·16	0·16	0·1	0·07	0·06
Plaster							
Gypsum on hollow tile	0·012	0·013	0·015	0·020	0·028	0·040	0·050
Lime on wood lath	0·048	0·020	0·024	0·034	0·030	0·028	0·043
Do. with finishing coat	0·036	0·012	0·013	0·018	0·045	0·028	0·055
Tiles							
Tile, West Point	0·012	0·013	0·018	0·029	0·040	0·048	0·053
Do. Pittsburgh	0·028	0·030	0·038	0·053	0·080	0·10	0·11
Do. acoustic	0·064	0·068	0·12	0·19	0·25	0·26	0·22

correction of auditoriums, though it is somewhat inferior in absorbing power. The hair-felt quoted in Table VII was specially prepared to resist moths: it was less expensive than jute-felt and much more absorbent. The presence of an air space behind the felt is seen to result in a perceptible increase in

TABLE VIII.—VARIATION OF ABSORBING POWERS OF OBJECTS WITH FREQUENCY

(W. C. Sabine : reverberation method ; square feet units)

Object.	Absorbing powers per object for frequency						
	64.	128.	256.	512.	1024.	2048.	4096.
Audience, per person . .	1·7	3·6	4·3	4·7	4·7	5·0	5·0
Chairs, bent ash . . .	0·15	0·15	0·16	0·17	0·18	0·20	0·23
Seat cushions—							
Cotton, under canvas and short nap plush . .	0·99	1·7	1·9	2·0	2·8	2·0	1·3
Hair, under canvas and plush	0·86	0·99	1·1	1·8	1·7	1·4	0·91
Hair, under canvas and thin leatherette . . .	0·67	1·1	1·3	1·9	1·3	0·73	0·43
Vegetable fibre, under canvas and damask . .	0·64	0·75	1·0	1·5	1·6	1·4	1·2

absorbing power, but the gain is so slight as to be incommensurate with the increased cost of construction and loss of durability.

In practice it is usually necessary to cover with some form of membrane any felt used for acoustic correction. Figures are given in Table VII for the effect of covering felt with certain membranes and also for the absorbing power of the membrane coverings alone. Table VII shows also that, as one

would expect, the membrane which has by itself the least absorbing power is the best covering to use over a highly absorbent material such as felt.

In view of the fact that in an ordinary rectangular room the efficiency of an absorbent is independent of its position, it is interesting to notice the fictitious values included in Table VII, which were obtained by Sabine in a room with a barrel-vault ceiling. Values obtained at the centre of the floor were unduly high and those at the sides were generally low, since the sound is focussed to the centre of the floor rather than to the sides.

Table IX relates to certain materials which were the subject of tests in England by the Building Research Station, the reverberation data being obtained by Barnett and Glanville in a large reverberant room having a volume of 9620 cu. ft. The duration of audibility of certain organ pipes was measured both before and after the introduction of about 100 sq. ft. of the test absorbent. Owing to lack of facilities at the time for calibration experiments, the results rested on the assumption (which was sufficient for the practical purpose then in view) that the standard initial intensity of the organ pipes was of the order of one million times that of threshold audibility: the authors at the same time indicated the degree of variations in the absorption coefficients due to possible variation from this standard. By the courtesy of the Director of Building Research, experiments were afterwards carried out with a loud-speaker source of variable intensity by Davis and Fleming,* of the National Physical Laboratory, to determine the rate of decay of sound in the same

* Davis and Fleming, *Phil. Mag.*, **2**, 51, 1926.

TABLE IX.—VARIATION OF ABSORPTION COEFFICIENTS WITH FREQUENCY

(Building Research Station results, modified : reverberation method)

Material.	Absorption coefficients for frequency					
	128.	256.	512.	1024.	2048.	4096.
Open window	*1·00*	*1·00*	*1·00*	*1·00*	*1·00*	*1·00*
Special Absorbents						
Slagbestos slabs, 1½ in. thick, ¾ in. from wall	0·32	0·38	0·65	0·73	0·30	0·29
Slagbestos slabs + canvas cover 1 in. distant	0·42	0·49	0·80	0·78	0·47	0·42
Cabot quilt, 3-ply, 2 layers 1½ in. from wall + canvas cover 1 in. distant	0·22	0·42	0·74	0·77	0·69	0·44
Hair-felt, 1 in. thick, 1½ in. from wall	0·09	0·25	0·43	0·63	0·33	0·35
Do. against wall	0·12	0·13	0·41	0·47	0·30	0·25
Canvas, 6 in. from wall	0·10	0·12	0·25	0·33	0·15	0·35
2-in. porous breeze concrete blocks, set in 1 : 3 cement-sand mortar	0·15	0·21	0·43	0·37	0·39	0·51
Panelling						
1-in. cork (coarse) slab (3¼ ft. × 1 ft. 7½ in.), 1 in. from wall, framed in wood	0·14	0·25	0·40	0·25	0·34	0·21
3-ply teak panels, 3 ft. × 2 ft. 2 in., 1 in. from wall, framed in wood	0·09	0·17	0·17	0·15	0·15	0·15
3/16-in. Celotex panels (8 ft. × 4 ft.), 1 in. from wall, framed in wood	0·09	0·17	0·19	0·14	0·19	0·16
Acoustic Plaster and Tiles						
Sabine plaster, ¾ in. thick (fixed as tiles)	0·07	0·07	0·23	0·43	0·27	0·41
Sabine plaster, 1 in. thick (as modified by B. R. S.), trowel applied	0·11	0·11	0·29	0·47	0·29	0·38
Akoustolith tiles, 1 in. thick	0·03	0·08	0·19	0·34	0·40	0·34

TABLE IX.—VARIATION OF ABSORPTION COEFFICIENTS WITH FREQUENCY—*continued*

(Building Research Station results, modified: reverberation method)

Material.	Absorption coefficients for frequency					
	128.	256.	512.	1024.	2048.	4096.
Floors						
Cork ¾-in. flooring slabs, glued down	0·08	0·02	0·08	0·18	0·21	0·22
Do. waxed and polished	0·04	0·03	0·05	0·11	0·07	0·02
Wood blocks, ¾-in. pitch pine, laid in mastic	0·05	0·03	0·06	0·09	0·10	0·22
Do. ¾-in. Gurjan, laid in mastic	0·03	0·04	0·07	0·14	0·09	0·15
Floor Coverings						
Carpet, pile, 1 cm. thick (1) on concrete	0·09	0·08	0·21	0·26	0·27	0·37
Do. (2) on felt, 0·3 cm. thick on concrete	0·11	0·14	0·37	0·43	0·27	0·25
Do. (3) on felt, on ¾-in. polished cork on concrete	0·17	0·14	0·35	0·42	0·23	0·34
Do. (4) on felt, on ¾-in. pitch-pine blocks on concrete	0·11	0·13	0·38	0·45	0·29	0·29
Carpet, Amritza, 1·1 cm. thick, on concrete	0·09	0·06	0·24	0·28	0·11	0·21
Do. Cardinal Batala, 1·1 cm. thick, on concrete	0·12	0·10	0·28	0·42	0·21	0·33
Rubber carpet (3/16-in.) on concrete	0·04	0·04	0·08	0·12	0·03	0·10
Do. on polished cork on concrete	0·09	0·04	0·15	0·11	0·10	0·04

room when empty. From this a deduction has been made as to the actual initial intensity of the sound set up by the several organ pipes in the Building Research Station experiments. The results, as modified in this way, are given in Table IX, in which

TABLE X.—VARIATION OF ABSORPTION COEFFICIENTS WITH FREQUENCY

(Stationary-wave method)

Material.	Authority.	Absorption coefficients for frequency			
		380.	512.	650.	800.
Asbestos roll fibre	Taylor	0·26*	..	..	..
Brussels carpet	Taylor	0·23*	..	..	..
Ceilinite	Taylor	0·25*	..	..	..
Compressed cork	Taylor	0·32*	..	..	..
Hair-felt, 1 in. thick	Taylor	0·51*	..	..	..
Smyrna rug	Taylor	0·26*	..	..	..
Quilted material	N.P.L.	..	..	..	0·47
Cane-fibre board, ½ in. thick	N.P.L.	..	..	..	0·23
Cork slab, 1 in. thick	N.P.L.	..	..	..	0·24
Felt ¾ in. thick	N.P.L.	..	..	..	0·14
Do. 1½ in. thick	N.P.L.	..	..	..	0·65
Do. 2¼ in. thick	N.P.L.	..	..	..	0·91
Akoustolith tile, cemented on 1-in. teak	Paris, Signals Experimental Establishment.	0·13	0·27	0·31	..
Acoustic plaster, cemented on 1-in. teak	Paris, Signals Experimental Establishment.	0·16	0·27	..	..
Sabine tile, cemented on 1-in. teak	Paris, Signals Experimental Establishment.	0·10	0·20	..	..
Acoustic plaster (3¾ parts slag to 1 part magnesite on 3 layers of 5-ply wood)	Paris, Signals Experimental Establishment.	0·18	0·25	0·27	..
Acoustic plaster (4¾ parts slag to 1 part magnesite on 3 layers of 5-ply wood)	Paris, Signals Experimental Establishment.	0·18	0·27	0·30	..
Acoustic plaster (6 parts slag to 1 part magnesite on 3 layers of 5-ply wood)	Paris, Signals Experimental Establishment.	0·21	0·31	0·36	..

* Frequency not stated.

the coefficients of absorption quoted are in general practically the same as those obtained by the Building Research Station for frequencies 1024 and 2048; greater by some 10 per cent. for frequency 512; and

TABLE XI.—VARIATION OF ABSORPTION COEFFICIENTS WITH FREQUENCY

(Bureau of Standards: stationary-wave method)

Material.	Absorption coefficients for frequency				
	297.	581.	1095.	2190.	2890.
Akoustolith	..	0·301	0·434	0·380	0·272
Brass	0·021	0·015	0·023	0·004	0·001
Brick	0·019	..	0·019	0·056	0·021
Celotex ($\frac{5}{8}$-in.)	0·058	..	0·056	0·072	0·097
Celotex B	0·178	..	0·399	0·734	0·708
Flax-li-num ($\frac{1}{2}$-in.)	..	0·229	0·312	0·503	0·336
Flax-li-num (1-in.)	0·182	0·422	0·456	0·569	0·407
Glass	0·021	..	0·020	0·010	..
Hair-felt, 1-in.	0·330	..	0·62	0·94 *	0·90 *
Insulite ($\frac{1}{2}$-in.)	0·056	0·102	0·182	0·256	0·172
Oak wood	0·011	0·007	0·011	0·006	0·005
Pine wood	0·012	0·009	0·016	0·016	0·009
Sound-absorbing tile No. 1	0·079	..	0·116	0·401	0·35
Do. No. 2	0·078	..	0·127	0·201	0·213

* The absorption at 2190 and 2890 frequency was measured upon a different piece of material from that used at 297 and at 1095 frequency.

less by some 15 per cent. for frequency 4096, 30 per cent. for frequency 256, and 50 per cent. for frequency 128.

Table X gives absorption coefficients obtained by the stationary-wave method by various observers, while values obtained by Eckhardt and Chrisler * of the Bureau of Standards, Washington, by the same method are given in Table XI.

Table XII gives data for the frequency 512(c^{ii}).

* Eckhardt and Chrisler, *Bureau of Stands. Sci. Paper* No. 526, 1926.

TABLE XII.—ABSORPTION COEFFICIENTS FOR FREQUENCY 512 (Watson)

Akoustolith	0·36
Carpets, unlined	0·15
Do. lined	0·20
Do. heavy, with lining	0·25
Celotex, ordinary, $\frac{1}{2}$ in. thick	0·31
Acousti-Celotex, $\frac{7}{8}$ in. thick, with 400 perforations per square foot, each perforation $\frac{1}{4}$ in. in diameter and $\frac{3}{4}$ in. deep, applied with perforations concealed	0·37
Acousti-Celotex (same as above) applied with perforations exposed	0·55
Acousti-Celotex, $1\frac{5}{16}$ in. thick, with 400 perforations per square foot, each perforation $\frac{1}{4}$ in. in diameter and $1\frac{1}{8}$ in. deep, applied with perforations exposed	0·70
Acousti-Celotex, $\frac{7}{16}$ in. thick, with perforations extending from face to back	0·40
Acousti-Celotex, $\frac{7}{16}$ in. thick, without perforations	0·25
Cheesecloth	0·019
Cocoa matting, lined	0·17
Concrete	0·015
Cork tile	0·03
Cretonne cloth	0·15
Curtains, chenille	0·23
„ in heavy folds	0·5 to 1·0
Flax, 1 in. thick, with unpainted membrane	0·55
Hair-felt, 1 in. thick, with unpainted membrane	0·55
Do. 1 in. thick, with painted membrane	0·25 to 0·45
Do. 2 in. thick, with unpainted membrane	0·70
Do. 2 in. thick, with painted membrane	0·40 to 0·60
Insulite, $\frac{1}{2}$ in. thick	0·31
Linoleum	0·03
Marble	0·01
Oil paintings, including frames	0·28
Stage opening, depending on stage furnishing	0·25 to 0·40
Ventilators (50 per cent. open space)	0·50
Wood, varnished	0·03

TABLE XII—*continued*

ABSORPTION BY INDIVIDUAL OBJECTS FOR FREQUENCY 512
(Watson: square feet units)

Church pews . . .	per seat	0·2
House plants . . .	per cubic foot	0·0031
Seats, upholstered, depending on material and lining .	per seat	1·0 to 2·5
Seat cushions, cotton, covered with corduroy . . .	,,	2·16
Seat cushions, hair, covered with canvas and light damask	,,	2·27
Settees, upholstered in hair and leather, seat and back	,,	3
Wood seats, for auditoriums .	,,	0·10

Some of the results are quoted by Heyl * as given on the authority of Watson. The method of measurement is not stated. The remaining results have been taken from a brochure issued by the Celotex Company in which Watson is again quoted as the authority.

Generally speaking, the results of the measurements of absorption coefficients by the various observers referred to above are in reasonably good agreement, particularly when the variety of sources of the materials is realised.

* Heyl, *Bureau of Stands. Circular*, No. 300, 1926.

CHAPTER VI

RESONANCE AND INTERFERENCE

Resonance and Forced Vibration

We have considered the progress of sound-waves proceeding outwards in all directions from a source and being reflected back from the enclosing surfaces. We have also considered the directing of these reflections and the methods by which they may be enfeebled. Other types of acoustical phenomena, namely, resonance and forced vibration, enable us to strengthen the source in certain cases and also to increase its effective area of vibration and radiation.

The magnitude of this effect is dependent upon the closeness of the coupling between the source and the connected system. The most efficient form of coupling is direct mechanical contact, such as that between the strings and the body of a violin. Pure acoustical coupling is also possible, such as that between a tuning-fork and a suitable resonating chamber in its vicinity. It is well known that the intensity of the emitted sound may be enhanced by the proximity of such a resonator. This arises from acoustical reaction upon the source, which facilitates the transference of vibrational energy from the fork to the air. In general, however, acoustical coupling is so weak that its effects are not

marked unless the resonator is close to the source and is particularly responsive to the frequency concerned.

As regards mechanical coupling, when an instrument (or even a singer or speaker) is in contact with a vibrant floor, energy is transmitted from the source through the contact, and the floor, thus set in vibration, emits sound. The energy comes from the source: the effect of a large surface in contact with the source is to increase the area of the vibrating body and so to facilitate conversion of its energy into sound. In large cathedrals it is noteworthy how often preachers prefer to speak from a temporary wooden pulpit instead of the less resonant pulpit of stone, marble, or the like.

Wooden panels and galleries are known to favour general audibility and, if a vibrant floor connected to the source were to be suitably connected structurally to such structures, further advantages should accrue. Because of the high speed of sound in solids—from 10 to 20 times the speed in air—such panelling, etc., would vibrate and emit sound almost as soon as the source. In the Leipzig Gewandhaus, beams are arranged to transmit the vibrations of the orchestra substructure to the wooden lining of the building, with consequent strengthening of the sound.

All systems, mechanical or aerial, which are capable of vibration have one or more natural frequencies to which they respond most readily. If the range of frequency of the source to which they are connected lies well above or well below the more prominent of these natural frequencies, then the influence of the connected system will be more

or less uniform over the range of the source. If, however, the natural frequencies lie within the range of the source, there will be an accentuation of notes lying near those frequencies. Resonance, which is the term applied to such sympathetic vibration, may be exhibited by columns of air, or by partitions, floors, ceilings, or other objects under the influence of a source of sound of appropriate pitch. The air of the room itself may respond particularly to certain notes, the pitch being higher the smaller the room. Such resonance would assist the source, but as its effects are limited to sounds within a restricted range of pitch, it will necessarily result in distortion or modification of music containing such notes. Doubtless in some circumstances this type of effect may be acceptable as a factor in music.

If a resonant panel is sufficiently large to have a very low natural frequency, or if for some reason it is heavily damped, selective effects will not be pronounced, and the strengthening of sounds will occur over a fairly wide range of pitch instead of being confined to notes within a narrow range. Undoubtedly this is the kind of effect usually desired in an auditorium. Distant vibrant or resonant materials not connected to the source cannot be expected to enhance the loudness; they can only absorb the sound through their vibrations, the degree of absorption being most pronounced for the natural periods of vibrations of the system. Distant panelling, for example, will thus absorb sound through its vibration, and if it is resonant will affect reverberation in a selective manner.

Interference

The phenomenon of interference gives rise to maxima and minima of sound distributed in a room when a simple source of sound is continuously maintained. It is difficult to see how such variations of loudness could be avoided in a room having reflecting surfaces, but fortunately the effects concerned are not of great practical importance. The actual distribution depends upon the shape and size of the room, upon the pitch and position of the source, and even upon the location of persons in the vicinity. The interference pattern may be very complicated where there are several sources of sounds.

With sustained notes rich in harmonics a noteworthy result of interference is that the fundamental may be heard at one point and an overtone equally clearly at another. In musical performances, however, where notes are rapidly changing, a steady interference system will rarely be set up, and the phenomenon is of no great importance compared with other factors which are detrimental to audibility in a room. Furthermore, the possession of two ears tends to nullify the results of interference, particularly where short wave-lengths are involved. As regards speech, the consonants which carry the essential characteristics are all more or less explosive sounds, so that interference phenomena are of negligible significance.

Sabine * has mapped out the distribution of intensity at head level for a sustained pure note in a room of rectangular plan with a barrel-vaulted ceiling, the radius of curvature of which was on the

* W. C. Sabine, *Collected Papers on Acoustics*, p. 152.

floor. His result is given in Fig. 52, contour lines being drawn for different intensities as in a geodetic survey. While this is of interest in showing how complicated an interference pattern may be, its

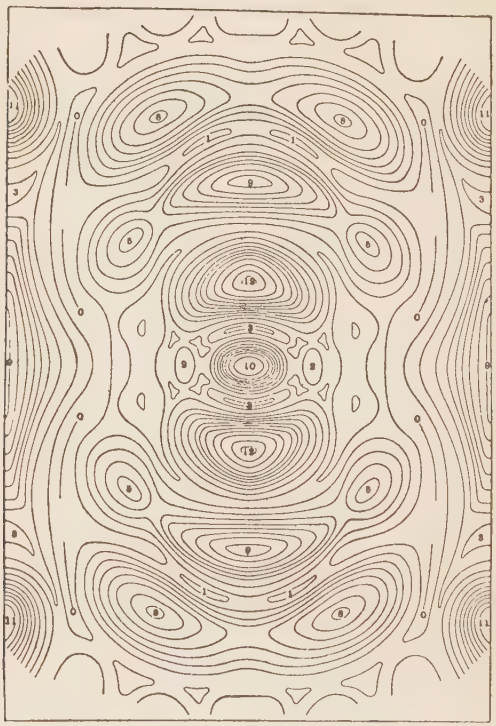


Fig. 52.—Interference pattern showing distribution of intensity at head level in a room with a barrel-vaulted ceiling with a centre of curvature at floor level (Sabine).

importance lies in the fact that it shows the greatest intensity of sound to be along the axis of the floor. Fig. 23 shows that sound is largely reflected from such a ceiling towards the centre of the floor, where as a consequence the interference maxima are greatest and the contour lines most closely packed.

CHAPTER VII

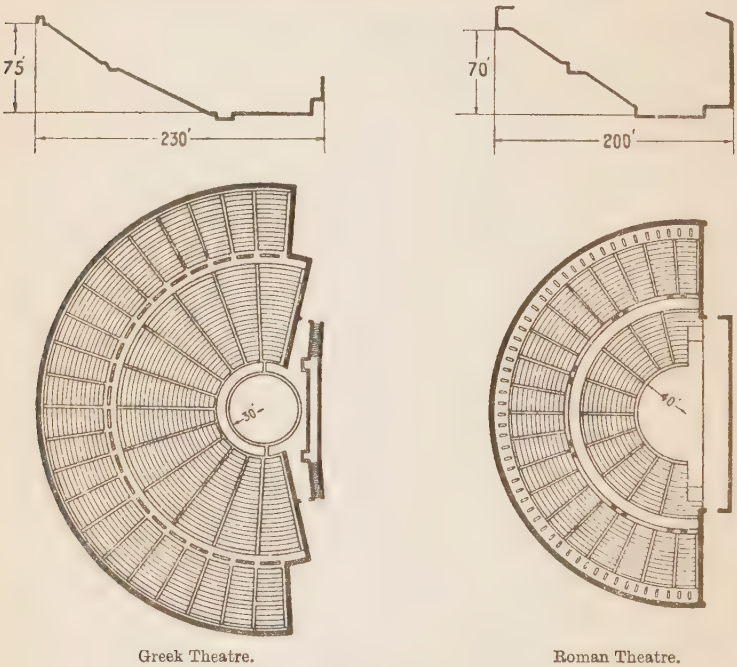
SPECIAL TYPES OF AUDITORIUM

Open-air Theatres

It is of interest to trace the development of the modern auditorium from the open-air theatres of classical times. In the open air, sound from a speaker reaches hearers mainly by direct radiation. It is clear that it will be to the advantage of the audience if it is accommodated on a terraced enclosure, and there is obvious benefit also in elevating the platform or stage on which the speaker stands. The boundary wall of the enclosure should embrace roughly the area normally reached by the human voice. These conditions were attained in the open-air theatres of the ancients.

In a Greek theatre, a modern example of which is to be found at Bradfield College in this country, the audience was accommodated on stone seats arranged on a terraced banking in a curve somewhat exceeding a semi-circle. The centre was occupied by a large circular space—the orchestra—on which the chorus with their leader were placed, and from which they sang. The chorus was originally the most important part of a Greek drama, and hence it occupied this central and most favourable situation for being seen and heard. Behind the orchestra was a shallow stage or logeion elevated to a considerable height.

This formed part of the roof of the skene provided for the accommodation of the actors and from which they emerged during the play. There is some difference of opinion among the authorities, but it appears probable that the actors performed



Greek Theatre. Roman Theatre.

FIG. 53.—Illustrating typical Greek and Roman theatres.

together with the chorus in the orchestra, and that only those representing the gods occupied the logeion. Fig. 53 gives an indication of the structure of a typical Greek theatre.

The theatres of the Romans were similar in general arrangement, but the terraced seats did not form more than a semi-circle. The orchestra, also semi-circular, was sunken somewhat and occupied by the audience. The actors performed on an elevated

stage which was of somewhat greater depth than the Greek logeion from which it was developed, the new arrangement conforming to the requirements of changes in taste and in dramatic literature. Fig. 53 shows a typical Roman theatre which may be compared with the Greek.

The earliest of these erections were of wood, but after a time in Greece the wooden theatres were replaced by stone or marble; though it appears that the wooden theatres persisted in Rome till a late period. According to Vitruvius, it was found that the stone structures did not afford that support to the voice which was a feature of the more resonant timber buildings, and the expedient was devised of introducing resonant vases, termed echeia. These are stated to have been situated in open-mouthed cavities prepared for them under the seats of the theatre, the capacity and form of the several vessels being so graduated that they would respond to a range of notes. Their value, however, in such a situation must have been distinctly problematical, and, considering sound as a form of energy, it is not clear how they could have increased the general audibility. Indeed, even the existence of these echeia has been disputed (none has ever been discovered), though it is significant that Vitruvius remarks that theatres built of wood do not require echeia.

From Fig. 53 it will be seen that the dimensions, particularly of the Greek theatre, were very considerable. In some, audiences up to about 20,000 could be accommodated. If the view is correct that the dramas of the Greeks were not spoken, but declaimed by a kind of rhythmical chanting, it may

be that the sonorous vowels of the Greek tongue conveyed the sense even to the remotest seats, perhaps 200 ft. away. Nevertheless, it seems certain that every possible reinforcement of sound was desirable, as the complete absence of reverberation gave no support to the voice. Wood surfaces in the proximity of the actors and a wooden floor might well have acted as resonators which were sufficiently close to the source to amplify the emission. Unfortunately, many of the details of the structure of these ancient theatres are controversial, but rebates are still to be seen between stone columns in the supporting wall of the stage which probably housed thin intercolumniations of wood. The small depth of the stage and consequent nearness of the players to the skene wall at their backs would ensure its efficiency as a reflector: the orchestra in front of the stage would undoubtedly be useful also, if it were unoccupied.

Lecture Theatres

In modern lecture theatres while the terraced seating accommodation of the ancient open-air theatres is usually retained, the acoustics are materially modified by the addition of a roof. As an example of a lecture room closely resembling the open theatres of the ancients, but on a smaller scale and with an added gallery, mention may be made of the theatre of the Royal Institution. Fig. 54 is a plan of this auditorium. It will be seen that generally the shape is semicircular, with a short extension towards the speaker. Thus the seats at the sides are rather closer to the speaker than the corresponding seats in front of him. To provide for the accommoda-

tion of apparatus, space is left in front of the lecture-table which, in order that experiments conducted on it may be visible to all, stands on the main floor and not upon a raised platform. None of the seats is at an excessive distance, and, as only about 2 ft. is allowed between successive rows, the theatre accommodates a fairly large audience (about 700)

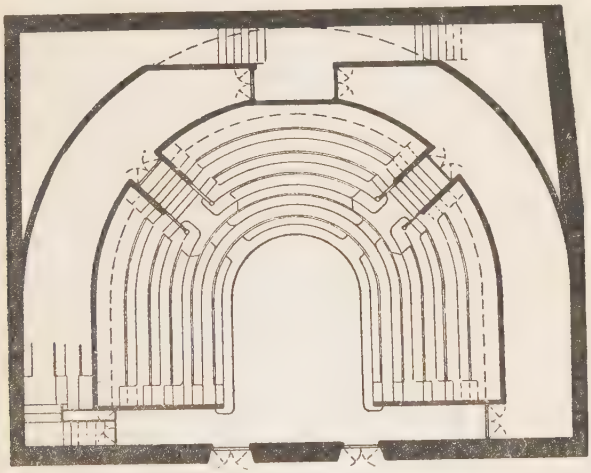


Fig. 54.—Plan of lecture theatre of the Royal Institution.

despite its moderate dimensions (height 30 ft., depth 45 ft., breadth 60 ft.). The theatre is constructed of wood, built within a cubical space enclosed by brick outer walls; staircases occupy the corner spaces between the semicircular sweep and the brick walls.

Fig. 55, Plate XIV (facing p. 106), is a photograph of a wooden model of the theatre kindly lent us by Sir William Bragg.

Fig. 56 (frontispiece), due to Mr Fleming at the N.P.L., shows sound-pulse photographs illustrating the progress of sound-waves in a central vertical

section of the R.I. theatre. Arrows have been drawn from the position of the source—the small circle represents the head of the lecturer—to indicate the general manner in which certain selected wave-fronts have progressed.

In a building with a moderately high ceiling, such as in this theatre, questions of reverberation and of echo may become of importance. While the ceiling is not sufficiently high for reflections from it to be markedly noticeable as echoes, a trained ear in the front rows of seats can detect the slight confusion associated with a just perceptible echo. Reflections from the walls behind the audience are directed upwards within rather confined spaces, so that no appreciable echoes would be expected to result. Generally speaking, all the sound which proceeds in a forward direction reaches hearers in the seats and is there largely absorbed. The sound-pulse photographs of Fig. 56 show, however, that the sound reflected from the upper part of the wall behind the speaker is finally returned to the floor after a second reflection from the ceiling, and probably contributes towards the echo effect perceptible in the front seats. This was confirmed by drawing sound-absorbent material across the upper part of the wall behind the lecturer when the slight defect in question was eliminated. An alternative treatment would be to splay the ceiling near the offending wall and so direct the sound to the back of the gallery, where it might be beneficial. A recessed circular skylight in the ceiling above the speaker is adjustable in height and, on the whole, does not seem to be acoustically a good feature; the recess tends to give an echo and to trap sound reflected

from the wall behind the speaker instead of passing it on to the back of the gallery.

These are minor criticisms, however, which mainly indicate that it would be inadvisable to provide a higher ceiling above the speaker. The theatre, which was built in 1800, was designed by Mr Webster (himself a student of sound) with, it is said, the assistance of Count Rumford and Sir Humphry Davy, and is of acknowledged acoustical excellence. Faraday, in 1835 in evidence before a committee of the House of Commons, at the time the rebuilding of the Houses of Parliament was being proposed after the fire of 1834, stated that he considered the Royal Institution theatre almost perfect for a single speaker. The only difficulty ever complained of is that a little effort is necessary on occasion to make the voice reach hearers in the remote seats under the gallery. Poor hearing is a common defect under the galleries of large auditoriums, but in this case the effect cannot be pronounced as the seats are only 40 ft. from the speaker. Such defect as there may be is probably because hearers are largely cut off from reinforcing reflections. In this respect auditors in the gallery are more happily situated, since they have the benefit of a reflection from the ceiling.

The period of reverberation of the theatre is quite short: approximate measurements give the standard Sabine period, when empty, as about 1·2 seconds, while calculations indicate that the period when the theatre is full of people would be about 0·7 second, very satisfactory figures due in great part to the absorbing power of the upholstered seating accommodation and of the floor carpeting.

The hall is acoustically very interesting for,

although the conditions are so good, certain defects appear to be just developing. From its behaviour one would infer that for the best audition in a theatre of this character hearers should not be at a distance greater than say 40 or 50 ft. from the lecturer, and that echo effects will begin to become perceptible if the difference of paths travelled by the original and reflected sounds exceeds about 60 ft.

University lecture theatres are usually rectangular in plan, but have the same arrangement of stepped seating, a very pronounced rake being preferred in some of the Scottish universities. Frequently the larger theatres are too reverberant except with a large audience. Where an audience is likely to vary considerably in numbers, upholstered seating is always desirable, for it makes the absorbing power of the hall less dependent upon the numbers present. In a university lecture theatre this point presumably does not arise, for small audiences would normally be accommodated elsewhere.

Another lecture theatre which may be mentioned is that of the Royal Society of Arts. This has stepped seating, of which the rake is slight. The hall is not of sufficient size for any troublesome echo effects to arise. Its reverberant condition is satisfactory, and the hall is regarded as pleasant and easy to speak in. The large canvas paintings which occupy the upper parts of the walls are undoubtedly useful in reducing reverberation and in suppressing to-and-fro reflection of sound which otherwise would be returned later to the floor after reflection from the ceiling; most probably too by their resonance to voice sounds, the paintings lessen the effort required in speaking.

The lecture hall of the British Institute of Radiology in Welbeck Street was originally the chapel of the Russian Embassy. Fig. 57 shows a plan and a longitudinal section through the dome of the hall.

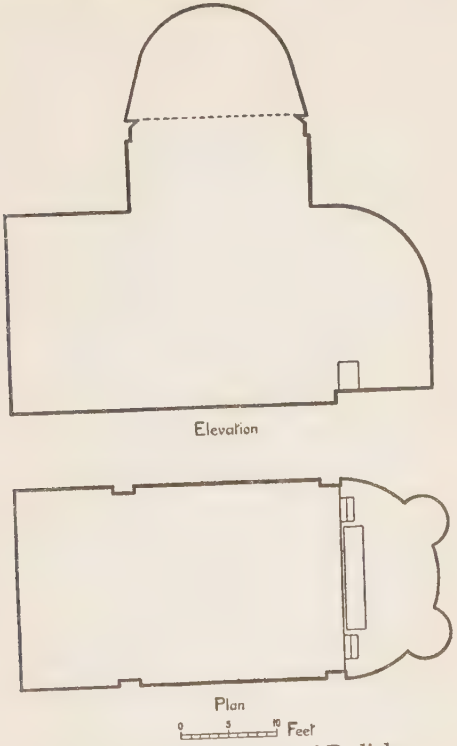


Fig. 57.—British Institute of Radiology.

Complaints were made of the poor acoustics of the hall when used for lectures, and a number of experiments were conducted in connection with it. The hall is not large and ordinary loudness of speech should be adequate, nor should there be troublesome echoes on first reflection. There is, however, likely to be some focussing of sound by reflection from the wall behind the speaker.

The following is the acoustic analysis of this hall in the condition in which it was first studied:—

British Institute of Radiology

Area and Absorbing Power of Surfaces

Volume 23,000 cubic feet.

Material.	Area. Square feet.	Absorbing power per square foot of material.	Total absorbing power.
Plaster and glass .	4021	0·03	121
Wood . . .	285	0·06	17
Oilcloth . . .	735	0·12	88
Chairs . . .	80	0·2	16
Total absorbing power with no audience . . .			242
" " " with an audience of 80 . .			602

$$\text{Standard reverberation period} = \frac{1}{20} \times \frac{\text{volume of room}}{\text{total absorbing power}} = \begin{cases} 4{\cdot}8 \text{ secs. empty.} \\ 1{\cdot}9 \text{ secs. full.} \end{cases}$$

These reverberation periods are somewhat excessive, particularly when it is realised that for some meetings the audience may be small and that good hearing is desirable where technical matter is to be followed.

A ripple-tank study indicated that sound entering the dome tends to be reflected to and fro within it, and then to be returned finally to the floor. The time occupied in this journey is sufficiently great for a slight echo effect to arise unless the sound has

been sufficiently enfeebled in its progress. The dome indeed increases reverberation and promotes echo; from an acoustic point of view, it is a feature which could be eliminated with advantage—a remark of very general application. It appears, however, according to the reverberation formula, that if a covering of an absorbent such as 1-in. hair-felt were applied to the dome and if heavy curtains in folds were used to cover the two end walls, a satisfactory condition (1·4 seconds empty; 1·0 second full) should be obtained. Also a heavy carpet on the floor instead of oilcloth would decrease the reverberation in the room, particularly when it is empty.

At present, however, full correction of the defect has not been attempted. About 1000 sq. ft. of celotex (p. 155) have been fixed to one end and the two side walls, and the period of reverberation is now estimated to be 3·0 seconds when empty and 1·5 seconds when full. This condition, while tolerable, is still rather too reverberant as judged by the accepted standards. Fig. 58, Plate XV, is a photograph of the hall after the walls had been panelled with celotex.

Theatres

In the modern theatre for dramatic performances, where it is necessary to accommodate as large an audience as possible within a satisfactory distance from the stage, the standard arrangement is adopted of several tiers of galleries one above the other. The seats nearest to the stage are definitely below the eye-level of the actors, and, consequently, it is not necessary for seats in the back rows to be very appreciably higher than those in front. There is

thus some saving in vertical space which is available for galleries.

In calculating the reverberant condition of the auditorium of a proposed theatre from a knowledge of the nature of its surfaces, it is, according to Watson,* sufficient to regard a normally equipped stage-opening as a large window in the auditorium with an absorbing coefficient of approximately 0·25. Values between 0·25 and 1, depending on the conditions and size of audience, may be taken for recesses beneath galleries in which the opening to the auditorium is small compared with the depth.

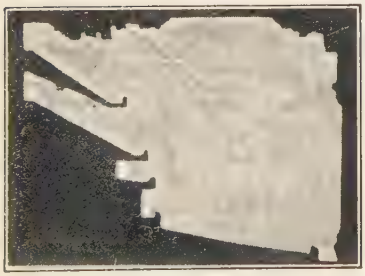
As regards echoes and reflections, the main ceiling of a theatre is usually lofty, and care must be taken that undesirable echoes and reflections from it are avoided, either by coffering or the use of absorbents. In this connection Fig. 59, Plate XV, due to W. C. Sabine,† shows sound-pulse photographs relating to a vertical section of the New Theatre in New York. The original wave may be seen proceeding into the two galleries. In the first photograph a marked reflection may be seen proceeding towards the fronts of these galleries: the second photograph shows how this undesirable echo was eliminated by installing a canopy in the ceiling. It will be recalled that Fig. 29 showed how, by modifying the ceiling, Sabine was able to avoid a similar defect which would have resulted from the execution of a first design of the Scollay Theatre.

Questions also arise as to the reflections from the side walls and from the fronts of boxes near the stage. Theatres are usually of somewhat compli-

* See Table XII. and Watson, *Acoustics of Buildings*, p. 49, 1923.

† W. C. Sabine, *Collected Papers on Acoustics*, p. 191.

FIG. 58.—British Institute of Radiology. See p. 137.
(*By permission of the Celotex Co.*)



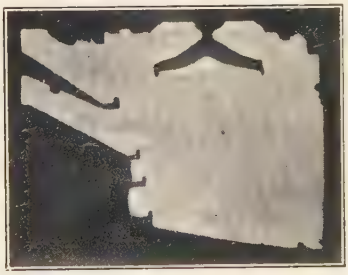


FIG. 59.—Sound-pulse photographs showing suppression of a ceiling echo in a theatre by means of a canopy (Sabine). See p. 138.

[*To face page* 138.

cated design, but a study of the progress of a sound-pulse in suitable model sections may be helpful in deciding whether certain features will give rise to undesirable reflections. The floor of the stage often serves as a valuable reinforcer of sound. Incidentally, a theatre audience is usually so closely seated as to form a valuable corrective on the reverberation.

Council Chambers

In legislative chambers different customs prevail in different countries. In some, all speeches are made from a centrally placed rostrum. In others, members stand up and speak from the position of their seats. When speeches are made from a central rostrum the acoustic requirements are very similar to those of a lecture theatre. The arrangement has the advantage that the audience is all in front of the speaker, so that suitable reflecting surfaces can be arranged near him to direct the sound. This system is the general practice in continental Parliament Houses. Many of these are of great height, and it is probable that they would not be satisfactory acoustically if used otherwise.

In the British House of Commons members speak from where they stand and do not proceed to a central rostrum. The House, the acoustics of which are generally regarded as excellent, is an auditorium upon which in its early history a considerable amount of thought was expended.

The House has a two-fold object: it exists for debate and also for the transaction of business. Much of the business is conducted in a conversational voice across the table, and it is therefore particularly necessary to ensure distinctness of speech,

free from reverberation and from echoes. When speaking, a member may have auditors behind him as well as in front, and the ceiling is the only reflecting surface which can be equally effective in reinforcing sound whatever the position of the member who is speaking.

These requirements are met by the present ceiling, which is non-absorbent and at a height not greater than 35 ft., so that its reflection provides useful reinforcement and not echo. Such a low ceiling is also advantageous in that, by diminishing the volume of the room, it reduces reverberation and promotes distinctness in hearing. When first used in 1848 the chamber was found to be accoustically defective, and in 1850 the ceiling was lowered by the introduction of the present inner false ceiling of glass. A great improvement resulted. It may be mentioned that the House of Lords retains its original ceiling and is generally regarded as acoustically defective.

As regards audition in the Press and Strangers' Galleries of the House of Commons, these are under the main ceiling and should derive benefit from a pronounced reflection, whereas the enclosed Ladies' Gallery will receive only an attenuated reflection. Fig. 30, Plate VIII, may be referred to in this connection. As regards reverberation, an estimate has been made of the period of reverberation of the House, of which the volume is about 127,000 cu. ft. Assuming more or less reasonable values for the absorbing power of the surfaces exposed, the estimated period of reverberation is 3·3 seconds when empty and 1·5 seconds if 570 persons were present.

The Hall of the House of Representatives of Rhode

Island State Capitol is quoted by Sabine * as an example where sound is reflected to and fro from wall to wall in moving upwards towards a ceiling. Sabine eliminated the reflections by applying felt to certain panels of the upper parts of the walls and covering the whole with decorative tapestry.

To ensure distinctness in a council chamber, every step should be taken to avoid excessive reverberation. Further, since the numbers present at various debates may vary considerably, the seats should be upholstered, so that the absorbing power of the room may be less dependent upon the number present which, as a rule, is small in proportion to the size of the room.

Concert Rooms

Concert rooms differ from the previous types of auditorium considered, in that a somewhat longer reverberation period is certainly tolerable, and to most people preferable. See Figs. 43 and 44 and Tables III, IV, and V. Insufficient reverberation results in a staccato effect which is not only displeasing to hearers, but is said to impart a sense of deadness and absence of power to the performers themselves.

Another point of difference is that an auditorium for orchestral or choral performances may be much larger than for speech, a greater volume of sound being available to give an acceptable loudness. The optimum volume depends upon the number of instruments or performers, with the proviso that if any large proportion of vocal solos is to be given in the chamber the size should naturally be limited.

* W. C. Sabine, *Collected Papers on Acoustics*, p. 137.

In Table XIII information is given (quoted from Heyl *) connecting the volume of a room with the maximum number of orchestral instruments suitable: no distinction is made between wind and string instruments, which are supposed to be present in balanced quantity.

TABLE XIII.—RELATION BETWEEN VOLUME OF CONCERT HALL AND DESIRABLE SIZE OF ORCHESTRA (HEYL)

Volume of room in cubic feet.	Number of instruments in orchestra.
50,000	10
100,000	20
200,000	30
500,000	60
800,000	90

There is some evidence that, as the intensity of musical sounds is increased, excess of reverberation becomes less tolerable. For example, a concert hall at the University of Illinois is stated to be too reverberant for speech—where distinctness is particularly desirable—satisfactory for violin and vocal solos, but too reverberant for music of greater intensity.†

The use of wood-panelling and other resonant materials is usually advocated for concert rooms, though the reason has not been thoroughly investigated. Resonant materials near a source may increase the volume of sound emitted, and it seems probable that a wooden panel, for instance, can

* Heyl, *Bur. of Stands. Circular*, No. 300, 1926.
† Watson, *Acoustics of Buildings*, p. 40, 1923.

respond to a considerable fraction of the range of musical pitch. On the other hand, it is known that the absorbent surfaces of a room frequently reduce the strength of the high notes more than the low ones, and suitable resonant panelling may counteract this.

In the case of orchestral music, it is found advantageous to have the wooden floor of the stage bare of carpet, in order that the sound from the instruments may be reinforced. Further, the region of the stage should be left reverberant to give the feeling of easy response desired by performers, whereas the auditorium should accord with the optimum condition for hearing, as previously discussed. Watson * quotes experiments in which absorbent material required by hearers to correct reverberation was objectionable to the performers until it was placed at the rear of the room, when both performers and hearers regarded the condition as perfect.

There appears to be no accepted criterion concerning the height at which a ceiling will give rise to a troublesome echo in the case of music. Since greater reverberation is permissible for music than speech, it may perhaps be inferred that a greater height of ceiling is also tolerable. However, with large concert halls, high ceilings may be considered desirable for the sake of appearance; in this event the ceiling and the upper portion of the walls should be acoustically absorbent. Similarly a distant back wall, if not obscured by a gallery or tiers of seating, should also be rendered absorbent.

If rehearsals are to take place in a concert hall provision should be made for a heavy curtain or

* Watson, *Science*, **64**, 209, 1926.

other device to separate the platform from the auditorium. Otherwise, owing to the greatly increased reverberation in the auditorium arising from the absence of the audience, performers will hear their music in circumstances acoustically very different from those which obtain with a full house.

Churches

In general, cathedrals and churches are characterised by a long duration of reverberation, arising from a large volume and a small absorbing power of the enclosing masonry walls. This condition dates back to medieval times and is responsible for the development of the characteristic features of church choral music and intoned liturgy. In some cathedrals the reverberation period may be as high as 6 or 7 seconds or more. Under such conditions staccato and other tempo effects in music are impossible, nor can ordinary speech, as in a sermon, be satisfactorily heard.

The requirements for church choral music and for the speaking voice are mutually conflicting. Wren, whose churches are generally recognised as very satisfactory acoustically, clearly recognised the difficulty. He refers in his writings to the noise and confusion which results in churches fitted as auditories, when the church is unnecessarily large; and goes on to say that "it should seem vain to make a church larger than that all who are present can both *hear* and *see*. The Romanists, indeed, may build larger churches; it is enough if they hear the murmurs of the Mass, and see the elevation of the Host." *

* *Parentalia*, p. 320; Elme's *Life of Wren*, p. 430; or Roger Smith, *Acoustics of Public Buildings*, p. 121, 1861.

In churches where reading and speaking are dominant factors in the services, the acoustic condition should obviously tend to conform to the optimum reverberant period already discussed. The speaker may occupy a position considerably above the level of his hearers, and the need, as in lecture theatres, for raising back seats above the level of front ones is obviated. Indeed, if hearers are all at the same level, and if there are no galleries, opportunities for personal display among the congregation are restricted and distractions are reduced.

In some forms of religious service, Testimony or Prayer may be uttered from any seat in the congregation. Thus some conflict of requirements may arise. If it is desired to hear the speaking voice, the usual acoustic conditions must, of course, be complied with, but it has to be recognised that spaciousness and pronounced reverberation are regarded by many as paramount requirements sanctioned by long tradition and usage. It may well be however, that, in the future, in seeking a compromise, the speaking voice will gradually receive more and more consideration, and a limited reverberation become usual.

In the United States, various churches have been corrected for excessive reverberation by the introduction of absorbent materials and the employment of the usual acoustic devices. W. C. Sabine,* in referring to his treatment of St Paul's Cathedral, Detroit, states that the nave, moderately narrow in the clerestory, was broad below owing to its extension by side aisles and could thus be treated as two simply connected spaces. For a full audience the

* W. C. Sabine, *Collected Papers on Acoustics*, p. 144.

lower space was adequately absorbent, but the clerestory was not. Highly absorbent felt was placed in panels in the coffered ceiling and the result is stated to be very satisfactory both acoustically and architecturally. The high and reverberant transept, and the central tower, were similarly treated. The chancel did not need, and did not receive, special treatment. It was high, suitable to the musical service, and being at the back of both pulpit and lectern did not greatly affect the portion of the service which called for distinct hearing.

Watson * mentions that the St James' Cathedral in Seattle was acoustically corrected with good results, the method being to regard it as four connected rooms. The sanctuary was treated with sufficient absorbent to make it suitable for speaking, the nave was left more reverberant for music, and the transepts were treated in an intermediate manner.

There is, however, another promising line of development by which speech may be sufficiently assisted, while a suitably reverberant condition of a church can be maintained. This is to employ for speech a number of electrical loud-speakers in various parts of the church which convey the speech from a microphone near the speaker to various positions in the congregation. The subject is dealt with on p. 159.

Radio Broadcasting Studios

Radio broadcasting studios also present a case for the accoustical control of reverberation. The requirements are somewhat conflicting, for while listeners using telephone ear-pieces will prefer a

* Watson, *Acoustics of Buildings*, p. 63, 1923.

certain amount of reverberation in the studio, those employing loud-speakers will themselves experience reverberation to a degree which will depend upon the size and acoustic condition of the room or hall in which the loud-speaker is situated. A compromise is therefore necessary. At present, studios are somewhat heavily damped, but there appears to be evidence that a slight amount of reverberation is better than complete "deadness." Presumably the compromise will move towards further reduction of reverberation in the studio if, as time goes on, there should be any considerable increase in the percentage of listeners using loud-speakers in reverberant rooms.

At the headquarters of the British Broadcasting Corporation at Savoy Hill * a fairly large studio (43 ft. by 20 ft. 6 in. by 22 ft. 6 in. high) is now in use for musical items. The ceiling is reasonably high, so that the ceiling reflection, owing to its somewhat late return, gives a slightly retarded reinforcement which is regarded as acceptable. The bare studio had a reverberation period of 7 seconds, before it was treated with absorbents. The walls are panelled with hair-felt $\frac{1}{2}$ in. thick, over which wall-paper decoration is applied, and the floor is heavily carpeted. Draperies on the ceiling are of the heaviest material available, and may be drawn aside if desired. The reverberation period of the chamber when fully draped is about 0·8 second, which can be increased to 1·6 seconds by drawing the ceiling draperies aside. The loftiness and scheme of decoration of the room are said to give a feeling of freedom which is much appreciated by the artists.

Ingenious attempts are also made to provide echo

* West, *Wireless World*, **20**, 225, 1927.

effects, largely for the purposes of dramatic performances, where differentiation between acoustical effects in, say, a room, a hall, or a cathedral is desirable. To this end communication is established through an open door with an echo room adjacent to the studio, and the music or speech is allowed to reverberate there. Two microphones are used, one in each room, and the proportion of "echo" can be controlled electrically to give realistic effects. Alternatively, the two rooms may be isolated from one another, the sound being introduced electrically into the echo room by means of a loud-speaker connected through an amplifier to the microphone in the studio. This loud-speaker provides the sound for the echo room, which sound is picked up by the second microphone, and added in varying proportions to the original sound from the studio. It may be noted that distortion introduced by these artificial methods of varying reverberation may be corrected to some extent in the echo-room amplifier. The echo room should be fairly large, as small rooms exhibit pronounced resonances within the music range.

Business Premises

Business premises frequently present a difficulty which may be met to some extent by treating the ceiling and walls with absorbents. In this case the object is not so much to control reverberation, as to reduce the general intensity of sound within the room. Where people are at work requiring mental application, for instance in banks, computing rooms, typists' rooms, or offices, quietness promotes efficiency and in some cases is essential. In hospitals,

too, quietness is especially to be desired. Cases also arise in which essential machinery, such as printing-presses, etc., causes unavoidable noise which is excessive for working conditions. Many such cases have been treated, particularly in America, by the application of suitable absorbents to suppress all reflected sound as completely as possible.

CHAPTER VIII

THE CORRECTION OF ACOUSTICAL DEFECTS

BEFORE discussing the correction of acoustical defects in buildings it is important to emphasise that acoustical requirements should be specially considered when any new building is designed, for undesirable features that could be avoided at the outset may prove difficult or impossible to correct after a building is erected. As in medicine, preventive acoustics is to be preferred to curative acoustics, but it is the latter which we shall now proceed to consider.

Echoes

We have already discussed echoes in Chapter III and have seen how, by a geometrical, sound-pulse, or ripple-tank study of sections, the general direction of echoes may be elucidated. Alternatively, the actual hall may be tested, for example, by the method which Watson employed to trace out reflections of the hiss of an arc lamp in a room (p. 59). By such means, an echo is sometimes found to be the cause of poor acoustics in certain parts of a hall.

The correction of echoes will depend upon their nature. Reference has already been made to the manner in which Sabine prevented an undesirable ceiling reflection in the New Theatre in New York by suspending a canopy from the ceiling. Similarly

the present false ceiling of the British House of Commons was introduced to reduce echo effects arising from too lofty a ceiling (p. 140). Alternatively, echoes may be reduced by covering the offending surface with a sound absorbent material: the ceiling, remote back walls, and the upper parts of side walls are frequently found to be suitable for such treatment. A similar remark applies to domes and barrel-vaultings. In certain cases, such as barrel-vaulting of great height and pronounced curvature, a useful temporary expedient is to hang a canopy of absorbent fabric at or near the focal region in order to absorb as much as possible of the ceiling reflection.

Reflections from plain surfaces present a rather definite wave-front. By introducing irregularities—such as coffering (p. 45)—this definite wave-front is replaced by a number of wavelets which scatter the sound in various directions. To have an appreciable effect on the reflection of sound, the irregularities must have a depth and width comparable with the wave-length of the sound concerned from say 1 to 3 ft. deep, and from 4 to 15 ft. wide. Such irregularities and coffering, while useful in themselves, frequently contribute to decorative effects when absorbents are applied, the absorbents being placed in the panel spaces.

Reflecting Boards

Attempts are sometimes made to improve the acoustics of a hall by introducing reflecting boards near the speaker. When successful these may serve a two-fold purpose. On the one hand, they may

hinder the direct progress of sound to regions from which echoes are likely to arise, and, on the other, they may reflect the sound into some region where it is needed. To be of value, however, very large surfaces are necessary; the reflectors commonly employed in practice have a value which is usually slight. Such benefit as may occasionally accrue is doubtless chiefly due to the reflection of the high-pitched notes which carry most of the characteristics of speech.

A parabolic form of reflector has been used from time to time, since—as far as optical laws are concerned—it reflects as parallel all incident rays which originate at its focus. For an ordinary sized reflector, however, sound will spread considerably outside the optical limits, and, indeed, the paraboloidal form could be replaced by some other curve without appreciable consequences. Watson reports a case in which such a reflector was mounted over a pulpit with satisfactory results. According to Roger Smith * (1861), an account of some experiments with a parabolic reflector in a church was published in London in 1829 by the Rev. John Blackburn of Attercliff, near Sheffield. The reflector had a diameter of nearly 12 ft. and a depth of 4 ft. It was claimed that through its use persons in the end galleries were able to hear even better than those at the sides near the pulpit. Following this experiment, an outline of which was communicated to the Royal Society in 1828, similar devices were introduced into at least thirty other churches. A favourable report of a trial at Cambridge was contained in a letter written by Professor Farish to the

* Roger Smith, *The Acoustics of Public Buildings*, p. 62, 1861.

Royal Society of Arts. The various reflectors were, however, ultimately dismantled. The chief objection to their use was that the speaker not only heard the echo of his own voice very prominently, but was subjected to the intolerable annoyance of hearing an accumulation of miscellaneous noises originating among the congregation.

Reverberation

The remedy for excessive reverberation in a room is either to reduce the volume of the room, say by lowering the ceiling and partitioning-off unnecessary large recesses, or to increase the sound-absorbing power of its surfaces.

The absorbing power of the surfaces is usually raised by the application of suitable absorbents to the walls or ceiling. In some cases, a canopy of absorbing cloth may advantageously be slung from the ceiling, particularly where the latter is of non-absorptive material and it is not desired to make permanent alterations for æsthetic or other reasons.

Values have already been given for the absorption coefficients of a number of materials in Tables VII to XII, and Sabine's formula (p. 68) permits the period of reverberation of a hall to be calculated from its volume and the absorbing power of its surfaces.

Besides being efficient as a sound absorber, a satisfactory material should be durable, fire-proof, and easy to clean. Felt may perhaps be taken as a representative efficient soft material. Ordinary builders' felt is not as clean as the better quality hair-felts which are obtainable (see Fig. 60, Plate XVI). As already remarked (p. 111), the absorbing

efficiency of a felt depends upon the flexibility of the mass as a whole and on its porosity. It is not dependent upon the material of the felt, except in so far as the nature of the material determines the closeness of the felting process. In this country felt is very subject to the attacks of moths.

Slag wool behind wire-netting is a good absorbent from the acoustical point of view: it is fire-proof and non-verminous, but somewhat harmful to the touch. Slag wool mixed with asbestos wool (slag-bestos) also makes a satisfactory absorbent. Another useful soft material is known as "Cabot's Quilt" (Fig. 61, Plate XVI): it consists of a loosely packed seaweed material, enclosed and quilted in a paper envelope: it is easy to apply and the material is not inflammable. Balsam wool is used in the States and is described as an efficient absorber which is non-inflammable (Fig. 62A, Plate XVII).

Practically all the soft absorbents are porous and require surface coverings. These should be as light as possible so that they do not reflect the sound, but transmit it to the absorbent beneath. Usually the absorbent is applied in panels behind a screen of canvas, net, or rep stretched within each section of the panelling. Painting the screen makes the surface covering more sanitary, but it reduces the absorbing power by as much as 15 to 50 per cent. for one coat, with a further but smaller decrease for a second coat. Stains are sometimes used, but there is a need for a paint for this purpose which is sufficiently light and flexible. As things are, when renewal is necessary, it is better not to paint the screen but to renew it.

Upholstered seating accommodation and furniture contribute usefully towards the absorbing power of

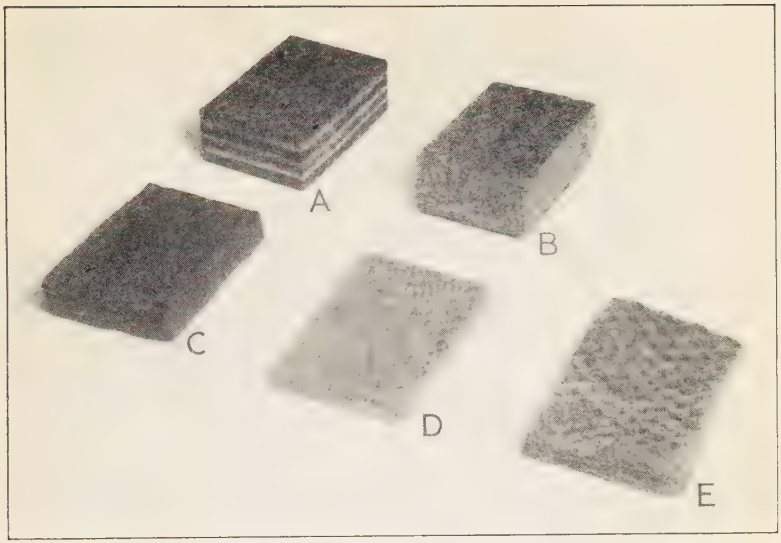


FIG. 60.

A and B. Vibration-absorbing combinations of cork and felt. See p. 171.
C and D. Good quality felts suitable for sound absorption. See p. 153.
E. Builders' felt.

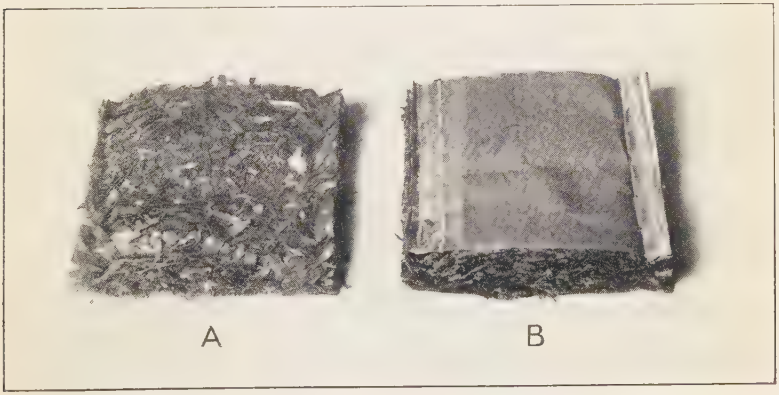


FIG. 61.

A. Cabot quilt with paper envelope removed.
B. Cabot quilt as commercially available. See p. 154.

[*To face page* 154.

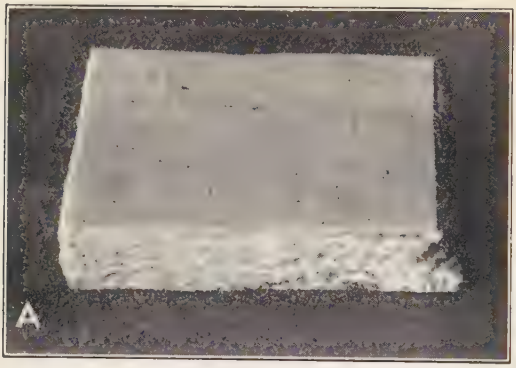


FIG. 62A.
Balsam wool with covering net.

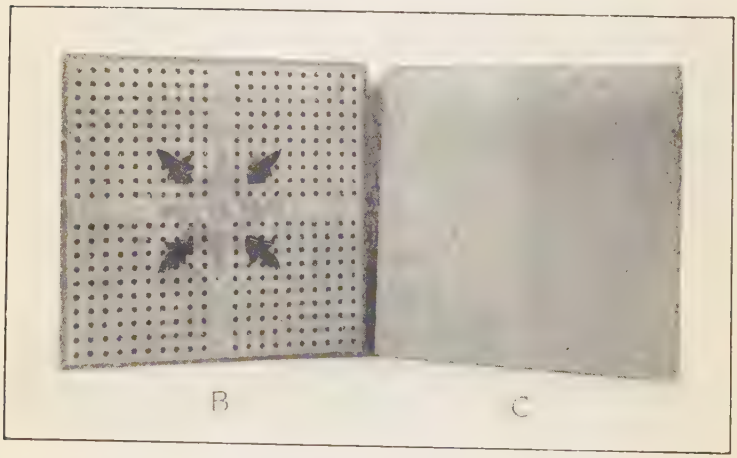


FIG. 62B AND C.
B. Acousti-celotex showing perforations and decorative effect.
C. Celotex. See p. 155.

[*To face page* 155.

a room; their effect is most valuable when only a small proportion of the maximum audience is present, the audience usually contributing the greater part of the absorbing power. Carpets on the floor have some value, as also have tapestries on the walls. Heavy curtains hung in folds are highly efficient as absorbents, but opportunities for their use are usually limited. Large unglazed canvas paintings have an appreciable value, and in the lecture room of the Royal Society of Arts several very large canvases occupy the whole of the upper parts of the walls, doubtless with material advantage.

Among hard materials, ordinary brick, plaster, and glass, hard wood, and similar materials have little absorbing power: in fact, as indicated earlier, they reflect sound more efficiently than the best reflector reflects light. Special forms of hard but porous material have been developed for acoustic purposes, among them certain fibrous boards of which a waterproofed cane-fibre board called "Celotex" (Fig. 62c, Plate XVII) may be mentioned. Published data attributed by the makers to Professor F. R. Watson indicate that a celotex board $\frac{7}{16}$ in. thick absorbs 25 per cent. of the incident sound energy. "Acousti-celotex" (Fig. 62B) is a perforated form containing numerous holes by which means the exposed area is considerably increased, and the absorbent value is raised. From the data the most efficient variety of acousti-celotex is $1\frac{5}{16}$ in. thick with 400 perforations per square foot, the perforations being of $\frac{1}{4}$ in. diameter and $1\frac{1}{8}$ in. deep, so that they do not pass right through the material. When mounted with the perforations exposed, acousti-celotex is stated to absorb up to 70 per cent. of the incident energy.

Even when the perforations are concealed, the absorbing power is claimed to be higher than that of the unperforated variety. Celotex is available in large sheets or in smaller "tiles" with square or bevelled edges, the tiles being convenient for treating curved surfaces. As with other fibrous boards, the decorative effect can be improved by stencilling, dyeing, or staining. The absorbing power of the acousti-celotex is not likely to be markedly affected by painting, provided the paint does not enter the holes.

Other interesting absorbents are the various acoustic or aerated plasters which have been developed. These contain a binder of magnesium oxychloride and have a spongy texture, arrived at either by mechanical frothing during mixing or by the addition of a gas-generating ingredient. In the acoustic plaster first patented by P. E. Sabine,* the basic material is granulated slag (from iron furnaces) prepared by dropping molten slag into cold water. The slag is broken up into small pieces by the expansive action of the steam. The principal advantage of the granulated slag is that the irregular shapes and sharp edges of the fragments make close packing impossible and result in the presence of numerous interstices. The bonding material used in uniting the particles is preferably magnesium oxychloride together with a small amount of glue or gelatine, the addition of which promotes the formation of foam in the plastic mass. The technique consists in mixing equal parts by measure of dry magnesium oxide with a solution of magnesium chloride in water (S.G. 1·17) containing 1 per cent. by weight

* P. E. Sabine, British Patent, No. 217,949 ; 2802/23.

of glue. The thin paste produced is then thoroughly stirred with the basic slag until the mixture is frothy. The colloidal nature of the bonding material results in the presence of a large number of minute air bubbles, which break as the plaster hardens, leaving the material full of minute pores.

A modification patented by Bakewell,* of the Building Research Station, consists in adding small quantities of hydrated lime and aluminium during mixing. The hydrogen liberated by chemical action quickly causes a foam to form. Although the hydrogen takes the place of glue as a froth producer, the glue may be retained with advantage to strengthen the foam. The ingredients may be mixed together in any suitable manner. One satisfactory method is to mix together magnesium oxide (200 grm.), slag (900 grm.), powdered aluminium or zinc (2·5 grm.), and lime (10 grm.), and then add magnesium chloride solution (250 c.c. ; S.G. 1·17), to which glue solution (10 c.c.) has been already added. The whole is then thoroughly stirred until frothy, when the plaster is ready for use.

Such acoustic plasters should not be allowed to stand after preparation, but should be applied at once. They adhere readily to wall or ceiling, are fire-proof, durable, and non-verminous. The surface forms a pleasing wall-finish where roughness is not taboo (see Fig. 48, Plate XIII, facing p. 102). The plasters are practically colourless, but tints may be introduced in the mixing if desired. The authors have no experience of the ability to withstand tremor when used for ceilings, or of the ease with which they can be kept free from dirt. Another absorbent wall

* Bakewell, British Patent, No. 252,459 ; 5472/25.

surface is "Akoustolith", which is a porous material consisting of grains of pumice bound together with Portland cement. In appearance it is somewhat similar to acoustic plasters, and it is available in tile form.

Absorption coefficients for acoustic plasters are given in Tables VII, IX, and X. As will be seen, they show a considerable superiority over ordinary lime plaster.

Stretched Wires

An old device, examples of which may still be found in this country, for the remedy of acoustical defects in a hall is a system of stretched wires in the upper part of the hall. Sabine * states, however, that such wires do nothing to reduce the chief acoustical defects—echoes and reverberation. He points out that if a violin-string were free from the sounding-board it would emit but little sound: the string itself cuts the air with but the slightest communication of motion, and, conversely, when a string at rest is subject to the action of the motion of air in a sound-wave there can be but little reaction tending to damp out the aerial motion.

Sabine states that in his experience systems of wires which have been set up have been found to be of little avail. He quotes cases where only a few wires were used, and cases where miles of wire were involved.

One must be careful to recognise, however, that the effects of wires need not necessarily be limited to those which arise directly from the reaction between the wires and air. For instance, it is

* Sabine, *Collected Papers on Acoustics*, p. 132.

evident that *stretched* wires could affect the natural period of ceiling surfaces if suitably attached, and could be arranged to communicate vibrations from surfaces in contact with the source to large ceiling areas at a distance. The effect would undoubtedly be difficult to control: it would be negligible as far as speech was concerned, and its perception would probably be limited to trained musical ears.

With this reservation that there may be possibilities which have not been explored, it is perhaps sufficient to state that, as far as we are aware, there is no recorded scientific evidence that wires have any beneficial effect in auditorium acoustics.

Electrical Amplifiers

The introduction in recent years of electrical speech-amplifying systems to facilitate the addressing of large audiences in the open air has been accompanied by a similar development for ensuring that speech shall be distinctly audible to all parts of large auditoriums. As already remarked the use of large buildings for speech is normally limited by the fact that adequate loudness cannot be attained at distances from a speaker very much in excess of 50 ft. Further, large halls are normally very reverberant, and if, as is usually the case, the ceiling is lofty it will not serve to reinforce the sound but, on the contrary, will produce undesirable echoes. The usual remedy for both effects is to introduce absorbent material—a procedure which, as we have seen, unfortunately decreases the volume of sound. But, by the introduction of the electrical amplifier, we are provided with a solution which may be possible

in some cases, and that is to use amplifiers to raise the volume of speech to the necessary level, and at the same time to reduce echoes and the reverberation period of the hall to such an extent that speech of normal rapidity can be heard without strain or discomfort. Unfortunately, there appears to be no published data for the optimum acoustical condition of an auditorium used in this way for amplified speech. However, there is sufficient experience to show that, at any rate, the problem of adequate loudness for very large auditoriums can be solved by the use of electrical amplifying equipment.

It has, of course, to be recognised that in the case of items of speech or music in which artistry or individuality or quality of tone are paramount features, the rendition of a loud-speaker outfit in its present stage of development may not be acceptable to a cultivated ear. It is possible also that the mere presence of a microphone a few feet away might react unfavourably on the freedom and style of a temperamental speaker to whom gesture and body movements are indispensable. Furthermore, all stray sounds originating near the microphone are normally picked up and included among the projected sound.

For natural effect the intensity at the ears of the listener must have approximately the same loudness as the original sounds at the microphone. Unnatural loudness results in apparent distortion of sounds, low-pitched constituents becoming unduly prominent. It is necessary, therefore, to amplify only to an extent such that remote listeners can just hear with comfort, and so to direct the projectors—which should be situated well above the

speaker's head—that the sound is not excessive for hearers near the platform. The majority of the audience will then have the impression of listening to only one source of sound—the speaker himself. Further, where a number of loud-speakers are used simultaneously, undesirable echo effects will arise if two instruments projecting into the same space are more than 75 ft. apart.

It should be clearly understood that the introduction of a loud-speaker equipment is not a cure for excessive reverberation. On the contrary, the enhanced loudness rather adds to the confusion which results from the delay in the decay of the sound.

A highly reverberant hall is undesirable for another reason. The increased loudness of the diffused sound contributes towards the most troublesome difficulty encountered in speech amplification, namely, the tendency of the apparatus to "sing" when sound from the projectors reaches the microphone with sufficient intensity and in suitable phase to aid the original sound. Even if a continuous note is not actually emitted, there may be distortion and lengthening when sounds of certain pitches are concerned. "Singing" can be suppressed by reducing the amplification, a cure which may, however, largely defeat the object of the apparatus. Usually the trouble is overcome by placing the microphone out of the direct beam of sound from the projectors, reducing the reverberation, and applying absorbents or draperies to any surfaces which reflect sound direct from the projectors back to the microphone. Fortunately, the difficulty is least pronounced in the presence of an audience, owing to the increased acoustical damping and reduced reverberation.

It is probable that hearing at considerable distances from a speaker (for example, at the back of large reverberant halls or in the transepts of churches) could be improved by mounting voice projectors fairly near to remotely situated hearers; nevertheless, it must be recognised that as remarked above this use is limited by the fact that if different projectors in a room are separated by considerable distances, effects of repetition similar to echo will arise.

Amplified speech has indubitably an advantage over normal speech in that the loudness is adequate without ceiling reflections, and, since the speech projectors are usually placed high above the speaker's head, late echoes from the ceiling are largely eliminated. However, for very high ceilings, additional absorbent will need to be introduced to keep the reverberation low. Thus it is still indirectly desirable to avoid a hall of great height. Moreover, a low ceiling will be required for ordinary speech if on occasion the amplifying system is not utilised for any reason.

In very large halls, the best situation for the platform and overhead projectors is in the centre of the hall. For halls of medium or small size the usual situations adopted are the middle of one side, and one corner respectively.

Speech projectors used in public-address systems are usually of the horn type, either circular and flared, or rectangular and straight. Dimensions at the wide end range from, say, 1 ft. 6 in. to 3 ft. 6 in., the length of the horn ranging from, say, 2 to 6 or even 10 ft. Horns of this type have a directive effect upon the emitted sound, and it is usual to depend upon them to cover an angle of about 40°.

Medium-size horns can be made to project sound a distance of 100 yd., and it has been claimed that the most powerful equipment can project to a distance of one mile. Horns of a folded type have been constructed in a box-like form which occupy less space than the foregoing. Hornless loud-speakers are also available. They are less efficient than the others with average speech, and have no appreciable directive effect, but they give better reproduction for low-frequency sounds.

A good arrangement for the loud-speaker is a cluster of horns high above the speaker and a few feet in front of him. About 25 ft. is a height which is usually sufficient to avoid "singing" in the open air. With very high ceilings the projectors should be proportionately higher. The cluster of horns is usually semi-circular if the platform is near one side of the hall, but circular if it is in the centre. The inclination of the loud-speakers should be such as to direct sound mainly to the parts of the audience out of range of the speaker's own voice, that is to say, to persons more than 50 ft. from the speaker. The transition should not be noticeable, and some freedom to adjust the inclination of the loud-speaker is desirable. Where a hall has a number of high galleries a double ring of projectors may be required, one inclined downwards to serve the body of the hall, and the other inclined upwards towards the galleries. It is sometimes possible to arrange special projectors to promote hearing beneath overhanging galleries, where hearing is often defective, but the practice is not recommended, and spaces inaccessible to the main projectors should be avoided when halls are designed.

It is important that the situation of the microphone should be as free as possible from extraneous noise, from echoes of the speaker's voice, from direct and reflected sound emitted by the projectors, and from general reverberation. In this way the magnification of unwanted sounds and the ever-present tendency to "sing" will be reduced. Heavy carpets on the floor of the platform—and perhaps an absorbent on the ceiling above—will reduce local reverberations and echoes between the floor and ceiling. Draperies suitably arranged behind the speaker may also be advantageous.

The microphone should normally be from, say, 3 to 6 ft. from a speaker and considerably more in the case of an orchestra. It should be mounted without attempts at concealment within boxes or other housings. Such housings tend to act as resonators for sound of appropriate pitch, and cause distortion. If there is a tendency to "singing" which cannot be suppressed by moving the microphone or by any of the devices already suggested, amplification may be reduced and the microphone put closer to the speaker. This, however, restricts the freedom of the speaker and is undesirable in a permanent installation. Examples of microphone mountings in harmony with their surroundings are shown in Fig. 63, Plate XVIII, and Fig. 64, Plate XIX, relating to Bath Abbey and Liverpool Cathedral respectively.

It is necessary to provide in the basement, or elsewhere, housing for the auxiliary amplifiers and batteries utilised in the equipment. Only a small room is required, say 10 ft. square or even smaller. Its position is immaterial, but it should be convenient

FIG. 63.—Showing microphone on pulpit in Bath Abbey.
See p. 164.
(By permission of the Marconiphone Co. Ltd.)

FIG. 69.—Sabine Acoustic Laboratory, Geneva, Illinois.
See p. 182.
(By permission of "Nature.")

[*To face page* 164.

Fig. 64.—The Bishop's throne, Liverpool Cathedral, showing microphone in position. See p. 164.
(*By permission of Standard Telephones and Cables, Ltd.*)

[*To face page* 165.

for charging the batteries, and for disposing of the fumes given off during this operation. The shielded leads from the microphone to the amplifiers should preferably be as short as possible, and should not run unnecessarily close to other electric wiring. In this way the risk is minimised of picking up electrical fluctuations which ultimately would be emitted from the projectors as hums and other noises. The microphone leads should run in a conduit separate from that conveying the leads to the loud-speakers, or the tendency to "sing" may be increased by electrical reactions.

In England the apparatus has so far been used notably in large cathedrals, *e.g.* Westminster Abbey and Liverpool Cathedral, speech projectors being mounted in suitable positions to deliver an adequate volume of sound to transepts and other "dead" spots. In Liverpool Cathedral—one of the largest cathedrals in the world—eight voice projectors are at present employed. Three are arranged to cover the choir and sanctuary; a fourth projects the voice into the memorial chapel transept; another into the south-eastern transept; two more into the area beneath the lectern, and another serves the annexe off the south-eastern transept. Fig. 65, Plate XX, shows two of the loud-speakers in position on the north side of the chancel.

A different type of amplifier equipment is that installed, for example, in the House of Lords. The House of Lords has a lofty ceiling and is somewhat defective acoustically, but the installation was not designed to overcome this difficulty. The primary object is to afford assistance to those members who, by reason of deafness, experience difficulty in hearing

the speakers. Loud-speakers are not utilised, but telephone ear-pieces are installed at thirty different points; twelve on each side of the House and six in the Press Gallery where, owing to the distance from the floor of the House, hearing is somewhat difficult. The microphones, three in number, are placed on the table of the House, one facing each side and the third facing the Woolsack. Their situation is thus especially favourable for the speeches of members who speak from the table and for the Speech from the Throne, though in fact speeches delivered from any part of the floor of the House are found to be effectively picked up by the microphones. A central amplifying system is used, and each user may adjust the loudness in his telephone to suit his personal requirements. The arrangement certainly improves audibility: it is useful for the Press and satisfactorily fulfils the main purpose for which it was intended. In view of the inconvenience of telephone receivers, it is, however, unlikely that the system would be regarded as acceptable by persons of normal hearing, as a general remedy for defective acoustics.

Another novel application is under trial by the International Labour Office at Geneva, as a step towards solving the language problem at international conferences.* During each speech interpreters deliver translations into microphones screened from the general auditorium sounds. These interpretations are reproduced at controllable strength in a series of specially sound-proof ear-pieces available for delegates requiring them.

* *Times*, June 6, 1927.

Fig. 65.—Voice projectors in Liverpool Cathedral. See p. 165.
(By permission of Standard Telephones and Cables, Ltd.)

[*To face page* 166.

CHAPTER IX

SOUND-PROOFING

General Principles

The question of sound-proofing is one of considerable importance in buildings, particularly in connection with the isolation of noise. It is especially desirable, for example, to provide quiet rooms in hospitals and office buildings, to insulate neighbouring rooms in schools of music and gramophone showrooms, and to exclude interfering sounds from telephone booths and from rooms where telephone messages are being dealt with.

The question is one of some complexity owing to the variety of paths by which an interfering sound may gain entrance to a room. For instance, if it originates in the air outside, it may enter through the material of the partitions, or through open windows or ventilating apertures. If the sound originates in the structure of a building, it may travel in the structure itself, particularly in a steel-girder building, and manifest itself unexpectedly in rooms very remote from the source.

The question of sound-proof constructions is a very wide one, and there is need of reliable data for many materials and proposed constructions for light partitions, etc. Methods of measurement and results at present available concerning air

to air transmission are dealt with in the next chapter.

Isolation from Air-borne Sounds

To prevent the entry of air-borne sounds it is only necessary to have walls sufficiently massive and rigid, and to avoid openings for pipes or ventilators. Generally speaking, where there is a choice, windows should be in the situation most conducive to quietness, opening for instance into a quiet outer space rather than into a noisy corridor. Doors and windows must shut completely, for the sound entering through cracks may be large relatively to that transmitted by other means.

It is not always realised that elaborate schemes for sound-proofing a room may be entirely nullified by omitting to obstruct all aerial paths, and in particular through an injudicious ventilation system. Sound travels along ventilation ducts almost as easily as along speaking-tubes. Ordinary bends and elbows in the ducts are quite ineffective in preventing sound transmission. In fact, conversation may sometimes be carried on between two separated rooms, using the ducts as a speaking-tube. It may be added that the air-stream in a duct offers no appreciable hindrance to the passage of sound, since the velocity of the air-flow is usually small in comparison with the speed of sound.

It is evident that, where especial precautions are taken to ensure acoustical isolation of rooms, particular attention must be paid to the ventilation arrangements. Ventilation ducts for individual rooms should not be branches communicating at once with a common main. It is more satisfactory

for each of the rooms to have its own independent duct communicating with a common distant chamber. It is further advantageous to line the interior of the ducts or chamber with sound absorbent. In the case of buildings in a smoke-laden town, however, such a procedure as regards the ducts is not very attractive. In such circumstances there are obvious conveniences in the alternative plan of fitting felt-lined baffles in suitable situations, and a case is on record in which decided improvement resulted from

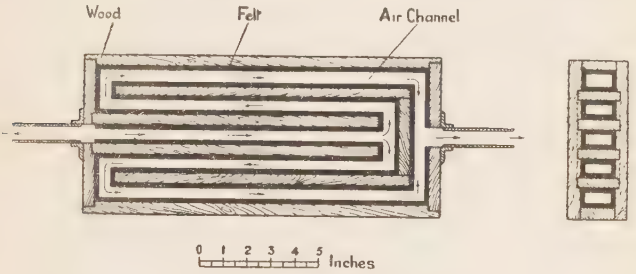


Fig. 66.—Silencer for air duct.

disposing the absorbent baffles in the remote chamber itself.

Fig. 66 shows a baffle-box in use at the National Physical Laboratory, which proves very effective in preventing the transfer of sound while readily allowing a stream of air to pass. It has, for example, been used to prevent the sound from an organ pipe being transmitted to an adjacent room along the air-supply pipe from a distant blower: in another case it successfully prevented the transference of sound from a noisy pumping device along the supply pipe.

Isolation of Air-borne Sounds by Partitions.

The transmission through walls and partitions of sounds arriving through the air may take place in two ways. On the one hand the incident sound may set the partition or wall in vibration as a whole, like a diaphragm, and so create sound-waves on the opposite side; on the other it may be refracted and set up a true sound-wave in the material of the partition, so that condensations and rarefactions are transmitted from particle to particle in the wall, and finally communicated to the air on the opposite side. For most walls true acoustical conduction is small, since the density and elasticity differ markedly from the corresponding properties of air: in other words, because the discontinuity in the path of the sound is so great. The greater part of the sound transmitted by a wall is by diaphragm-like vibration, the effect being most pronounced for thin walls and resonant sounds. Thus, to arrest sounds arriving through the air, it is only necessary to have walls sufficiently massive and rigid for vibration as a whole to be rendered negligible, and to avoid openings for pipes or ventilators.

Isolation from Structure-borne Sounds

As regards sounds which originate in the structure of a building, whether arising from motors, lifts, and attached machinery generally, or from musical instruments in contact with floors, it is necessary for effective insulation to break up the continuity of the structure. In some cases discontinuity is attained by interposing layers of felt, or sand, in

suitable positions in the path of the sound. It is essential, however, that where such layers are used no bolts or tie-pieces must bridge the insulating layer, otherwise the sound-proofing measures will be nullified.

Frequently the simplest place to introduce absorbent is at the source. Motors and machinery, whether on springy supports or otherwise, may be insulated from the floor by substantial layers of materials, such as cork, felt, or rubber. Where bolts must pass through the insulation, these can be insulated by bushing, and by using insulating washers under metal ones. Very heavy machinery requires special insulation and a separate foundation.

Felt-like insulation may also be introduced into the actual structure of a building, to assist in isolating noise. For instance, a wall may be insulated from the floor upon which it stands by means of a layer of felt, and a further layer may be used to insulate it from the ceiling. Laminated combinations of felt and cork are commercially available, which are specially designed for isolating vibrations, will set with any form of concrete or cement, and consequently can be embedded in floors, etc., if desired, by applying them before hardening commences. In steel constructions suitable insulating material can be employed as a bedding for foundations, or interposed between columns, girders, cross-beams, etc., to counteract the transmission of sound which would otherwise occur. (See Fig. 60, Plate XVI, facing p. 154.)

In insulating rooms such as music studios, the most effective plan appears to be for the boundaries of each room to be double, the inner shell being

insulated from the outer. In fact, each room should be constructed more or less as a complete inner box, floating upon suitable insulation on the structural floor or joists, and insulated from the structural walls and ceiling. Nails or screws should not pass from one shell to the other, and, in cases where connection cannot conveniently be avoided, full use should be made of insulating bushes and washers.

Sound-deadening Partitions

As regards walls, we have noted the desirability of double-wall constructions for excluding structure-

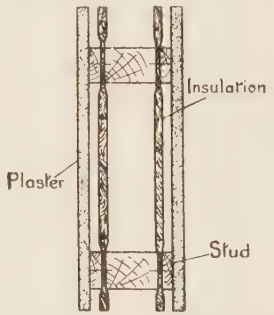


Fig. 67.—Light sound-deadening partition.

borne sounds. Heavy rigid masonry offers the best obstruction to sounds arriving through the air. Where the suppression of all entrant sound is essential, double masonry walls upon separate foundations should be adopted as in the Sabine laboratory (p. 182).

It is frequently necessary, however, to make even light partitions as sound-proof as possible. The usual principle is to have double walls as completely isolated from each other as can be arranged, and to fill in the space between them with sound

absorbents or insulators. For instance, slag wool may be placed in the space between the studs of a double match-boarded partition, the match-boarding itself being fairly thick—say $\frac{3}{4}$ in.—and insulated from the studs by strips of felt or other insulation.

Fig. 67 shows a method of making light plaster partitions with sheet-felt or quilting as insulator. It will be seen that the insulation is so arranged that rigid connection between members is reduced to a minimum; in the intervening spaces the insulation acts both as an obstacle and as an absorbent.

Sound-deadening Floors

The communication of sound from a floor to the ceiling below may be largely reduced by placing strips of felt, fibre-board, or indiarubber upon the joists before the floor is laid.

Sometimes an inner floor upon sleepers is floated upon a layer of sheet-felt, fibre-board, or quilting insulation resting on the usual concrete or wooden floor. Slag wool is used in a somewhat similar manner, the inner floor being insulated from its sleepers by strips of felt, and the space between the floors being filled in with slag wool or slag-bestos.

In the case of a wooden floor an alternative arrangement may be adopted to save space. The inner floor is dispensed with, felt, fibre-board, or indiarubber is inserted between the joists and the usual floor-boards, and slag wool is packed beneath the floor-boards either to the full depth of the joists, or to a smaller depth of say 3 in. In the latter case, small fillets of wood are nailed to the sides of the joists 3 in. below the floor-boards, and rough boarding

or wire-netting is nailed to them to support the slag-wool insulation. Again, considerable resistance to sound is offered by constructions in which the floor and the ceiling below have separate joists: for convenience, and to reduce the depth of the floor, the ceiling joists are placed to alternate with the floor joists.

Sound-deadening Ceilings

In sound-deadening ceilings slag-wool slabs may be nailed to the under-side of the joists, and the ordinary lath and plaster ceiling applied to fillets of wood nailed through the insulation to the joists to receive it. Fibrous plaster slabs may also be used instead of the lath and plaster ceiling.

Felting, quilting, or fibre-board may be applied in a similar manner between the joists and the finished ceiling. A number of alternate layers of insulator and furring will increase the effectiveness: in this case no nails should pass right through all the layers of furring, but each layer should be nailed only to the one above it.

Sound-proof Doors and Windows

The transmission of sound through a closed door is a matter for measurement by the methods discussed in the next chapter. We may notice here the absolute necessity for a good fit and a tight closure. A good door closure can be obtained, as in telephone-booths, by using a seating of felt or of rubber tubing, and a lever door-handle to press the door upon its seating and so close all cracks. Windows in sound-proof doors or partitions should be double, the glass panes being set in felt-like material.

Lift-shafts, Heating-pipes, etc.

Every endeavour should be made to avoid heating or other pipes entering a sound-proof room from the outside, as they may transmit sound and defeat the various sound-deadening precautions. Where such entry cannot be avoided it is desirable to set the pipes in some insulating material within wall cavities, so that vibrations cannot easily be communicated to the walls from the pipes, or to the pipes from the walls. Further, radiators connected to the heating-pipes should not be fixed to thin floors, but should be bracketed say to rigid outside walls, preferably with insulated bolts. Similarly, ventilation ducts should be insulated from walls and, if necessary, from the ventilating fans by means of a length of flexible tubing. Lift-shafts should be as rigid as possible and insulated from the main structure of the building: they should be surrounded by corridors and stairs and should not be adjacent to rooms where quietness is desired.

Illustrations

The National Institute for the Blind, 224–228 Great Portland Street, presents an interesting case of the application of the above principles.* An essential feature was the provision of an organ, an instrument upon which blind musicians frequently excel, and it was required that no sound should penetrate to the offices above and below.

The building is of steel-framed construction, and, as a first step, the floor of the music-hall is formed

* *Architect*, **97**, 118, 1917.

as an independent raft of steel-framing with hollow brick panels entirely insulated from the main supporting cross-girders by pads of compressed cork 2½ in. thick in metal frames, and from the walls by a 2-inch space packed with slag wool. Upon this raft the walls and ceiling of the hall are erected in light steel framing standing clear of the surrounding structure and lined internally with plaster slabs with slag-wool backs. The upper slabs are finished in fibrous plaster and Keene's cement, the lower are covered by oak panelling. The floor is covered with compressed cork slab ¾ in. thick overlaid with thick cork-carpet, while the portion under the organ itself is covered with compressed cork slabs 2½ in. thick with cork pads in metal frames under the heavier portions.

The walls and other surfaces of the main structure surrounding the inner shell are padded throughout with two thicknesses of Cabot's quilting, while round the organ chamber, for which an independent wood lining was preferred to plaster, two layers of quilting were attached to the main structure and a third layer was fixed to the back of the lining.

The windows are double, the outer forming part of the main structure in the usual way, and the inner being attached to the independent lining and glazed with leaded lights bedded in felt.

The result is stated to be so satisfactory that in the rooms immediately below, it is impossible to detect a sound of the organ, which is a three-manual instrument containing over forty stops. When the hall is in use the ventilation is entirely mechanical, fresh air being drawn from the roof, and foul air extracted through perforations in the ceiling.

Another interesting building of which details have been published * is the Music School of St Paul's Girls' School, Hammersmith, completed in 1913.

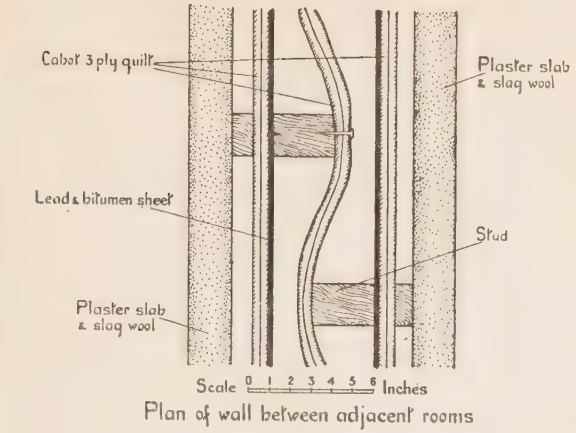


Fig. 68.—Sound deadening in music-practice rooms. St. Paul's Girls' School, Hammersmith.

The building consists of a large hall for singing, two large rooms for chamber music and nine or ten practice rooms on the top floor for piano and violin playing. It is claimed that the practice rooms have

* *Architect*, **90**, 568, 1913.

been so satisfactorily insulated, that it is impossible to hear any sound either through the floors or the partitions.

Fig. 68 shows the details of the floor and wall of a practice room. Each room is practically an insulated box, wrapped in two layers of Cabot's quilt and lead and bitumen sheeting. The floor rests upon sleepers insulated from the joists by further layers of quilt. The joists themselves form part of a wooden raft which is insulated from the structural ferro-concrete floor by pads of "Mascolite." The inner finish of the walls of the insulated box consists of plaster on slag-wool backing. Great care was taken in the construction, even the nails securing the work being in some cases insulated with rubber. Double doors and windows were used throughout.

The rooms are ventilated by means of fresh-air inlets, with outlets in every room communicating with an exhaust-fan chamber in the roof. The ducts from each room are arranged to prevent the transmission of sound, use being made of inlet and outlet ventilators, constructed much like the silencer of a motor car, the baffles being made in felt and perforated lead. The ventilating shafts are made of "Mascolite" felt.

CHAPTER X

THE MEASUREMENT OF SOUND TRANSMISSION THROUGH PARTITIONS

Sound Transmission through Partitions

We have seen that the transmission of sound through partitions may take place either by vibration of the partition as a whole, like a membrane, or by true acoustical refraction whereby condensations and rarefactions are transmitted from particle to particle in the wall and finally emerge on the other side.

Rayleigh * has shown that the fraction of incident sound energy reflected in air from a rigid non-absorbent material is given by

$$\frac{\pi\rho_1 l/\rho\lambda}{\sqrt{\{1+\pi^2(\rho_1 l/\rho\lambda)^2\}}},$$

where ρ_1 is the density of the material of thickness l, ρ the density of air, and λ the wave-length of the sound. The remainder of the sound is refracted and transmitted and, on calculation, is found to be exceedingly small. For instance, assuming reasonable values for the properties of mahogany, it is found that a board 2 in. thick would, if rigid, transmit only about twenty parts in one million of incident sound at a frequency of 700 vibrations per second, and less at higher frequencies.

* Rayleigh, *Theory of Sound*, 2nd edit., **2**, 88, 1896.

Thus, as we have already remarked, refraction effects may usually be ignored in practice, and we need consider only the diaphragm-like vibrations. In this connection, we may note that the natural frequency of any partition depends not only upon its nature, mass, size, and shape, but also upon the nature of the clamping at the edges. For a 2-in. mahogany board having dimensions of 6 ft. $\times$ $4\frac{1}{2}$ ft. and rigidly clamped at its edges, the gravest mode of vibration would have a frequency of about 65 vibrations per second. For a reinforced concrete wall 9 in. thick and 15 ft. $\times$ 10 ft. in size, the frequency would be about 50.

It may be noted that, when the natural or resonant frequency of a diaphragm is much lower than the frequency of the incident sound, its behaviour will depend mainly upon its mass. On the other hand, when the natural frequency is much higher than that of the incident sound, the stiffness of the diaphragm will be the preponderating factor. Incident sounds with a frequency in the region of the natural frequency will result in very large amplitudes, the extent of which will depend upon both the mass and stiffness and also upon the damping. Indeed, the resonant frequency is determined solely by the stiffness and mass, and at this frequency it is the damping alone which restricts the amplitude to finite dimensions. These facts follow readily from the usual mathematical equations for maintained forced vibration.

Thus, when a given material is employed as a partition, its resonant frequency and the sound transmission through it will depend, among other things, upon its size and upon the nature of the clamping of its edges. Accordingly it is desirable that

transmission tests should be conducted on samples having a size and method of fixing comparable with those normally employed in buildings. Large specimens and large scale work are necessitated, and a description will now be given of the most important methods at present in use.

Sabine Reverberation Method of Measuring Transmission

In the Sabine * reverberation method of measuring transmission the partitions are built into an aperture in the sound-proof wall between two adjacent, but structurally separate, rooms. Broadly, the method consists in producing a sound of constant intensity in the larger and more reverberant sound-chamber and then, by stopping the source, allowing the sound to decay at the rate natural to the room until it ceases to be audible in the test-chamber on the other side of the partition. The intensity of the sound in the sound-chamber at this instant is estimated from reverberation measurements in the source-chamber, and is taken to be numerically equal to the reciprocal of the coefficient of transmission of the partition. In actual operation note is made of the duration of audibility both in the source-chamber and in the test-chamber on the other side of the partition.

In work of this character, in which thick masonry partitions may be tested, it is, of course, essential that no sound should be transmitted from one room to the other except *via* the test material. It is very desirable also that external noises should be effectively precluded, for otherwise they will

* W. C. Sabine, *Collected Papers on Acoustics*, p. 237.

interfere with measurements of the duration of audibility of the test sounds. To provide satisfactory experimental conditions, the Wallace Clement Sabine Laboratory was designed and erected in 1918 at Riverbank, Geneva, Illinois (some thirty-odd miles west of Chicago), by Colonel Fabyan. It embodies the ideas arrived at by the late Professor W. C. Sabine after successful preliminary work in the Jefferson Physical Laboratory.*

The Sabine Laboratory.

The Sabine Laboratory was designed largely for the determination by reverberation methods of both

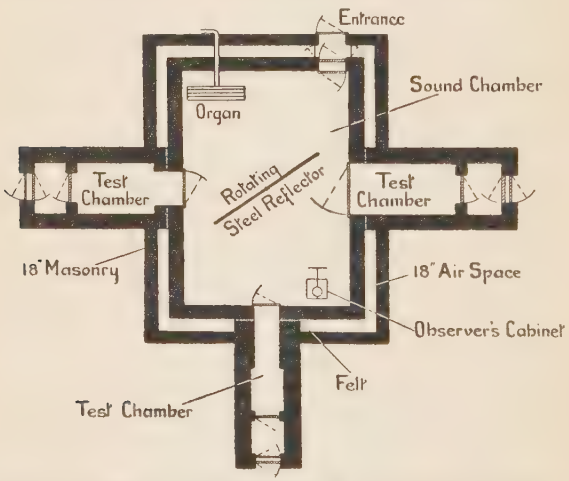


Fig. 70.—Plan of sound-chambers in the Sabine Laboratory.

absorption and transmission data for materials. Fig. 69, Plate XVIII, facing p. 164, is a view of the building, Fig. 70 is a plan of the essential parts, and Fig. 71 is a section. For simplicity, the office and workshop accommodation has been omitted from the

* P. E. Sabine, *Amer. Architect*, July 30, 1919.

plan. The main features are the sound-chamber and the three test-chambers. These rest upon entirely separate foundations, to prevent transmission through the structures. The layer of felt shown between two adjoining walls serves to exclude sound from other parts of the building rather than to insulate the test-chambers from the sound-chamber.

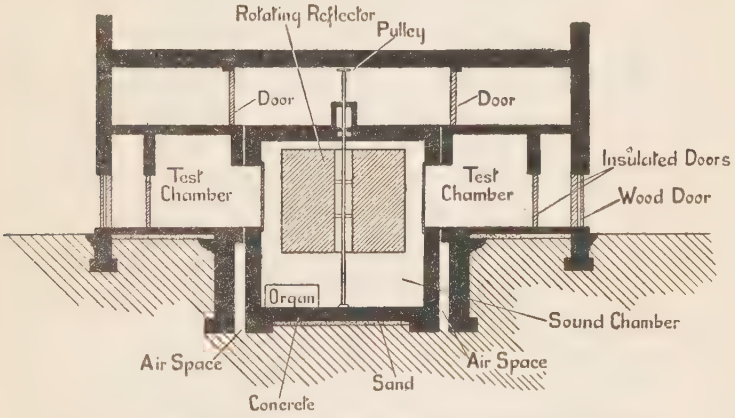


Fig. 71.—Section of sound-chambers in the Sabine Laboratory.

The sound-chamber is a rectangular room, about 27 ft. × 19 ft. × 20 ft. high, built within and completely insulated from the outer shell of the building. Its foundations consist of successive layers of concrete, tarred paper, concrete, tile, and sand to minimise the conduction of sound through the earth. The chamber has four openings: one to each of the test-chambers, and an entrance doorway in the basement. The entrance doorway is closed by a triple door, the two outer being of heavy steel and the middle wooden one of heavy "ice-box" construction. The test-chambers are each entered by means of a small vestibule having two sound-proof doors.

When the sound-chamber is being used for absorption tests (p. 93) all the openings are closed by heavy steel doors, so that the room then has the advantage of constant acoustical properties—an essential feature when an extended series of investigations is involved. When transmission tests are being carried out, the steel door leading into one of the test-rooms is replaced by a panel of the test material.

The walls of the sound-chamber are lined internally with wood-fibre plaster, and the room has a standard period of reverberation of 12 seconds for sound of frequency 256 vibrations per second. The very low absorption of the chamber itself makes its acoustical properties very sensitive to changes, and increases correspondingly the precision with which measurements can be made. A large steel reflector, mounted on a shaft at the centre of the room, revolves noiselessly and assists in varying the interference system, so promoting a uniform distribution of sound intensity throughout the room, and averaging the incident intensity on the test partition.

The source of sound is an organ of seventy-three pipes (frequency range 64 to 4096), each specially constructed to give as pure a tone as possible. The organ is operated electrically by an observer seated in a wooden cabinet, from which a chronograph may also be controlled. The motor and blower are mounted upon separate foundations with an intervening air-cushion and layers of felt to lessen the vibration communicated to the earth. Sound-conduction through the air-supply to the organ was avoided by lining the air-ducts and air-reservoir with felt and by hanging a felt baffle in the air-chamber.

In this laboratory P. E. Sabine * has conducted transmission experiments on the lines of the earlier work of the late Professor W. C. Sabine. As stated earlier, the method is to sound the organ pipe and to measure the duration (t_1) of audible sound in the sound-chamber after the pipe ceases. Under identical conditions the duration (t_2) of the sound heard in the test-chamber through the partition is also measured. The ratio of the initial intensities of sound in the two rooms is then given by

$$\log_e(I_1/I_2)=A(t_1-t_2)$$

where A is the rate of decay of sound in the sound-chamber, and is measured in the manner set out on p. 91.

Sabine found that changes in the acoustic condition of the test-room had some effect upon the duration of audibility observed within it, though the effect was not marked if the observations were confined to positions near the transmitting panel. He consequently adopted this procedure, and for safety in any series of tests kept the condition of the test-room constant. Sabine expresses his results in terms of the ratio (I_1/I_2) of the initial intensities in the two rooms. This he calls the "reduction factor" for the test partition.

This reduction factor does not give directly the coefficient of transmission of the partition. Davis † has shown that if the observer is so placed that the ear perceives only the sound entering the test-room and none of the scattered reverberant sound

* P. E. Sabine, *Amer. Architect*, July 28, 1920; Sept. 28 and Oct. 12, 1921; July 4, 1923; *Phys. Rev.*, **27**, 116, 1926.

† Davis, *Phil. Mag.*, **50**, 75, 1925; **2**, 543, 1926.

within it, then the reciprocal of the reduction factor

$$I_2/I_1 = \tfrac{1}{4}k$$

where k is the coefficient of transmission for the partition, *i.e.* the fraction of the sound energy transmitted through the partition. If, however, the ear in the test-chamber perceives only the reverberant sound which arises from repeated reflections within this room, and if the test-chamber were sufficiently less reverberant than the sound-room, the ratio would be kW/a_2S_2 instead of $\frac{1}{4}k$, where W is the area of the test partition, and a_2S_2 is the total absorbing power of the test-chamber. In this case, the dependence of the result upon the characteristics of the test-chamber is evident.

Buckingham * and Davis † have each discussed a modification of Sabine's method in which both rooms may be large, and in which either the source-chamber or the test-chamber may be the more reverberant. Measurements in the test-chamber would be concerned with the reverberant sound; the method has, however, not been tested.

Transmission through Flexible Materials.

Figures for the sound reduction factor of various thicknesses of felt have been read off from graphs obtained by P. E. Sabine ‡ to cover a range of notes of different frequency, and are given in Table XIV and Fig. 72. In the test, specimens 84 in. × 36 in. were mounted in suitable frames and set in the test-

* Buckingham, *Bur. Stands. Sci. Paper*, No. 506, 1925.
† Davis, *Phil. Mag.*, **50,** 75, 1925; **2,** 543, 1926.
‡ P. E. Sabine, *Amer. Architect*, Sept. 28 and Oct. 12, 1921.

aperture: precautions being taken to avoid cracks. Fig. 72 shows that, for a given note, each added layer of felt reduced the transmitted sound approximately in the same ratio, though the straight lines when produced do not pass through the value unity for zero thickness of felt. Sabine suggests that surface phenomena in transmission by felt may explain this, but it would appear from the analysis

TABLE XIV.—SOUND TRANSMISSION THROUGH FLEXIBLE MATERIALS (P. E. SABINE)

Material.	Layers.	Sound reduction factor (I_1/I_2) for frequency					
		128.	256.	512.	1024.	2048.	4096
Hair-felt (each layer 1 in. thick, weight 9 lbs. per cubic foot).	1	3·1	2·9	4·0	5·2	4·6	7·9
	2	4·4	4·4	7·2	13	13	23
	3	5·8	6·6	11	26	36	49
	4	7·3	13	23	63	87	140
"Doublet" of hair-felt and heavy paper (hair-felt as above); weight of paper, 0·095 lbs. per square foot).	1	10	8·4	8·4	200	470	..
	2	17	26	34	2,200	14,600	..
	3	32	35	58	11,500	65,000	..

indicated above that the divergence might arise from the conditions of the experiment.

Corresponding results for one, two, and three "doublets" or composite layers of hair-felt and heavy paper are also given in Table XIV. The presence of the paper markedly decreases the transmission. When the results are studied, it is found that later layers do not have quite the full effect of earlier layers, and further that the total transmission through a number of doublets is less than that

calculable from the properties of the paper and felt components considered separately.

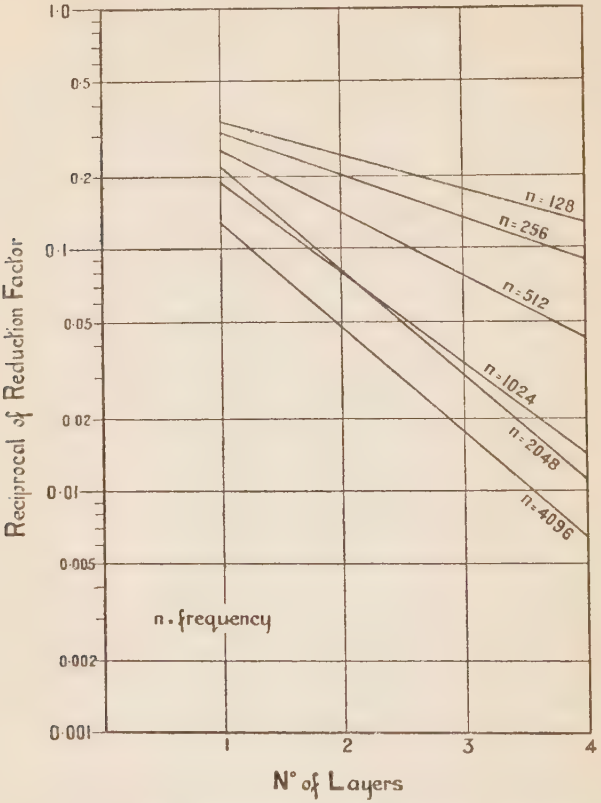


Fig. 72.—Sound transmission through hair-felt at various frequencies (P. E. Sabine).

Transmission through Windows.

Reduction factors obtained by P. E. Sabine * for various window constructions are exhibited in Table XV. All were tested in the same sash, the total area being 79 in. × 31 in. In one case a single pane window was used, the pane filling the sash.

* P. E. Sabine, *Amer. Architect*, July 28, 1920.

In others the sash was subdivided into two, four, twelve, and even more panes, and it was thus possible

TABLE XV.—SOUND TRANSMISSION THROUGH WINDOWS AND DOORS (P. E. SABINE)

Construction.	Sound reduction factor (I_1/I_2) for frequency						
	64.	128.	256.	512.	1024.	2048.	4096.
Windows 79 *in.* × 31 *in.*							
$\frac{1}{8}$-in. glass, 12 panes	60	49	68	140	380	230	150
$\frac{3}{16}$-in. plate glass, 4 panes	200	110	79	260	320	120	620
$\frac{3}{16}$-in. triplex glass, 4 panes	190	56	23	180	280	160	360
$\frac{3}{16}$-in. glass, small-leaded panes	130	84	100	270	1100	600	400
$\frac{3}{16}$-in. plate glass, 2 panes, single glazed	73	53	39	93	290	180	72
$\frac{3}{16}$-in. plate glass, 2 panes, double glazed, set in putty	80	63	91	320	540	300	220
$\frac{3}{16}$-in. plate glass, 2 panes, double glazed, set in felt	89	70	91	360	1700	1200	590
$\frac{1}{4}$-in. plate glass, 4 panes	240	210	120	440	560	190	710
„ „ „ single pane	170	150	120	200	320	80	600
Doors 79 *in.* × 31 *in.*							
Light birch veneer, 4-panel	22	20	41	110	190	160	66
Solid oak, $1\frac{3}{4}$ in. thick, with cracks as ordinarily hung	18	14	32	110	160	42	57
Solid oak, well seasoned and air-tight	50	32	66	190	370	330	210
Solid oak, swollen with dampness	200	100	80	190	370	410	630
Double-wall "cold-storage" door, 4 in. thick	26	44	120	510	870	780	760
$\frac{1}{4}$-in. solid steel	580	320	490	1300	4400	1400	830

to estimate the effect of the additional bracing due to the framework of the panes. Different thicknesses of glass were used, and also a triplex material consisting of two sheets of $\frac{1}{16}$-in. window glass sealed together with an intermediate thickness of

celluloid, the whole forming a $\frac{3}{16}$-in. pane of approximately the same mass as ordinary plate.

Among interesting features of the table we may note in the case of the 4-pane windows that the $\frac{1}{4}$-in. plate glass was an appreciably better sound insulator than the lighter $\frac{3}{16}$-in. plate glass; and that the $\frac{3}{16}$-in. triplex was less effective than the $\frac{3}{16}$-in. plate glass in preventing transmission. Provided we are dealing with rigid partitions, discontinuities of density and elasticity increase insulating powers. However, in this case we are undoubtedly dealing with flexural vibrations of the panes as a whole, and the decrease in rigidity occasioned by introducing the celluloid more than offsets the value of the discontinuity.

Some other noteworthy points in Table XV concern the effects of double-glazing a window. The construction tested had two panes, each being 31 in. $\times$ 39 in. The figures show results for a single-glazed window and also for the same window double glazed, that is, with glass set on both sides of the sash and 1 in. apart. The sound insulation afforded by the double glazing falls far short of what would be expected if the second pane reduced the sound intensity in the same ratio as the first. Evidently the vibration of the first pane is transmitted directly to the second through the sash, and the air-space is thus rendered ineffective. The effect of attempting to insulate the two panes by setting the second in $\frac{1}{2}$-in. saddlers' felt instead of putty is also shown. For lower frequencies the device is almost without effect, but some improvement is manifested at higher frequencies.

The effect of varying the number of panes in the

sash is also illustrated in Table XV. For the lower frequencies the heavier glass is generally more effective than the lighter, in spite of differences in constructional details of the window. At higher frequencies the well-braced lighter constructions of small panes of $\frac{1}{8}$-in. or $\frac{3}{16}$-in. glass are generally as effective in reducing the transmitted intensity as the heavier $\frac{3}{16}$-in. or $\frac{1}{4}$-in. glass in larger panes. Discussing the results, P. E. Sabine states that for low frequencies the reductions of intensity are in the same order as the masses of the various partitions, whereas at higher frequencies the stiffness of the construction appears to be the more important factor.

It is dangerous, however, to generalise further from these instances, for, as pointed out on p. 180, mathematical analysis of the forced vibrations of a simple system indicates that, contrary to the above order, it is when the forcing frequency is *high* that the mass of the vibrating system is of greatest importance, the stiffness being paramount for low-frequency forcing. It seems better to assume that the natural frequencies of windows may fall within the range of acoustical frequencies and that the general superiority of a heavy glass window may be vitiated by resonances. Such resonances may be of two kinds; on the one hand the whole window construction may vibrate as a unit, and on the other, individual panes may respond singly to the forcing frequency. The commonly accepted fact that glass panes sometimes break under the influence of sustained notes sung by powerful singers is probably due to such resonance by single panes.

Transmission through Doors.

A number of doors of widely different construction were also tested by P. E. Sabine,* all being of the same size 79 in. × 31 in. The results are given in Table XV. Precautions were taken to prevent transmission of sound through cracks or openings of any kind. In ordinary practice, of course, doors and windows are not closed in an air-tight manner, and, as a measure of the effect of such incomplete closure, it may be noted that figures are given for a $1\frac{3}{4}$-in. solid oak door as ordinarily hung upon hinges, and for the same door sealed in. The increased deadening effect is most marked.

Of sealed doors the inferiority of the light-panel construction is evident. An interesting revelation is the superiority of the $\frac{1}{4}$-in. steel door over the complicated "cold-storage" door 4 in. thick.

With respect to the $1\frac{3}{4}$-in. solid oak door, it will be seen that the state of seasoning affects the transmission. Starting with the dry door fitted air-tight, the transmission was reduced for both high and low tones when the door was swollen through dampness. The dry well-seasoned timber showed more uniform response over the whole range of tones. This is of general interest, since it may explain why a well-seasoned old violin gives a better performance than a "green" instrument of recent make.

Transmission through Masonry Partitions.

Plaster walls of three types were tested by P. E. Sabine † in a uniform size of 8 ft. 2 in. × 6 ft. 2 in.,

* P. E. Sabine, *Amer. Architect*, July 28, 1920.
† P. E. Sabine, *ibid.*, July 4, 1923.

namely, gypsum tile—both solid and hollow—hollow clay tile, and solid plaster on expanded metal. The plaster applied in each case to these bases was unfibred gypsum plaster mixed in equal parts with clean sand.

As regards the plaster on expanded metal walls,

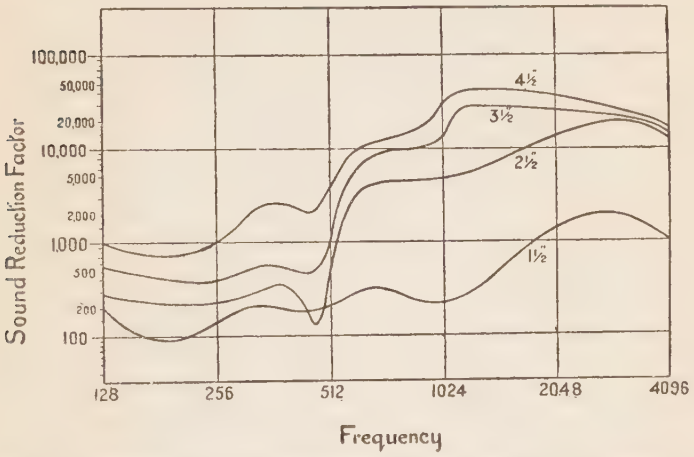


Fig. 73.—Intensity of sound transmitted through partitions of plaster on metal lath (P. E. Sabine).

the results obtained were of the type indicated by Fig. 73, where it will be seen that the curves are somewhat irregular. Presumably the minor fluctuations of the curves are due to resonances in the partitions. The dip near frequency 512 was not affected by altering the size and absorbing power of the test-chamber. The general characteristics of the partitions were obtained by smoothing out the minor inequalities and so deriving the figures given in Table XVI.

As regards the masonry partitions, the results for the gypsum and clay tiles (both solid and hollow)

were studied as a whole to ascertain whether mass, stiffness, or damping was the most important factor.

TABLE XVI.—SOUND TRANSMISSION THROUGH MASONRY PARTITIONS (P. E. SABINE)

Partition.	Wt. per sq. ft.	Relative stiffness.	Sound reduction factor (I_1/I_2) for frequency					
			128.	256.	512.	1024.	2048.	4096.
2-in. solid gypsum tile, unplastered	lbs. 10·4	..	66	66	94	350	620	720
2-in. solid gypsum tile and ½-in. plaster	15	..	150	120	290	1,200	2,300	2,200
2-in. solid gypsum tile and 1-in. plaster	19·6	..	200	250	540	4,800	5,700	2,600
2-in. solid gypsum tile and 1¼-in. plaster	21·4	84	200	260	580	5,600	6,700	3,000
3-in. solid gypsum tile, unplastered	14·2	..	88	81	160	2,100	3,400	1,500
3-in. solid gypsum tile and 1¼-in. plaster	25·4	130	280	390	1300	10,000	10,000	2,400
3-in. hollow gypsum tile, unplastered	11·1	..	79	74	120	700	1,000	780
4-in. hollow clay tile, unplastered	17	..	270	250	400	3,500	980	610
4-in. hollow clay tile and ½-in. plaster	22	..	310	260	460	6,700	2,600	1,100
4-in. hollow clay tile and 1-in. plaster	27	..	530	470	1000	9,100	9,100	2,200
4-in. hollow clay tile and 1¼-in. plaster	28·8	120	670	540	1400	1,100	10,000	2,300
1½-in. solid plaster on expanded metal	13·9	1	200	140	210	210	1,400	1,000
2½-in. solid plaster on expanded metal	23·2	17	280	220	530	4,800	14,000	12,000
3½-in. solid plaster on expanded metal	32·5	77	550	390	6700	14,000	25,000	15,000
4½-in. solid plaster on expanded metal	41·8	..	1000	1000	3900	32,000	37,000	17,000

Relative stiffness was estimated by subjecting one side of the walls to small pressures and measuring

the displacement of the middle point. No feasible way was found of measuring damping. In order to have a single numerical value as a measure of the reduction of sound intensity, the value of the logarithm of the reduction factor was averaged for all

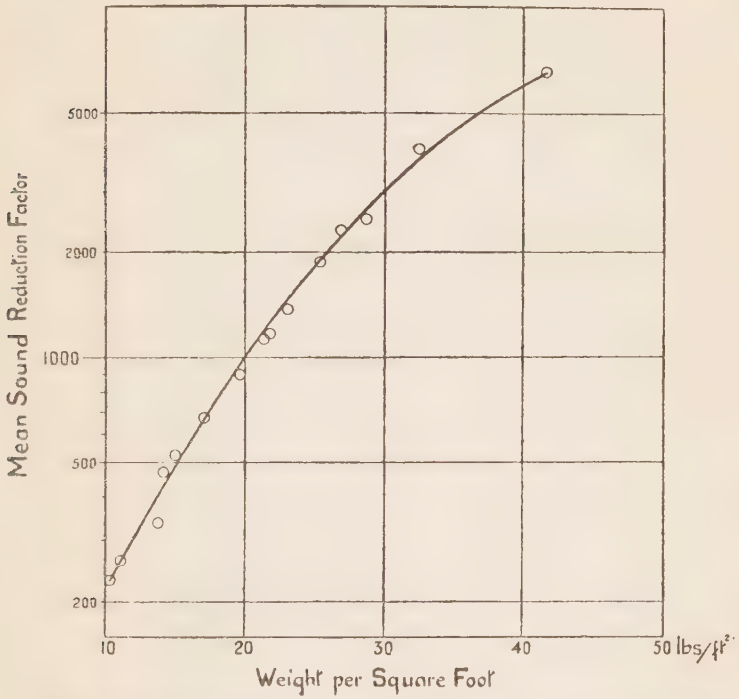


FIG. 74.—Intensity of sound transmitted through masonry partition (P. E. Sabine).

the frequencies used. It was found that the averages for the different materials were not in the same order of magnitude as the stiffness figures, but there was a close relation between the reduction of sound intensity and the mass of the partition of whatever type, as shown in Fig. 74.

Generally speaking, therefore, as regards sound

insulation, the important factor in respect to the various constructions discussed is the weight.

It is noticeable that reduction in sound intensity is greater for frequencies above about 512 than for those below. In one case a smaller wall (3 ft. × 8 ft.) was tested and the results showed that, on the whole, the reduction of tones for frequencies below 512 was appreciably more for the smaller than the larger wall of equal thickness, but that for higher tones the results were not appreciably affected by a change of area.

All these facts are consistent with the supposition that for masonry partitions the resonances are fundamentally of very low frequency. In consequence, transmission is greatest for tones of low pitch, since flexural vibrations are greatest for frequencies near the resonance region. Also, as stated earlier, if the resonance region is of very low frequency, it is the mass rather than the stiffness which controls the response to external excitation of relatively high frequency. Finally, if the area of the diaphragm is decreased its natural frequency will be raised nearer to the frequency of the incident sounds, with a consequent increase in transmission for the lower tones.

Transmission through Double Walls.

Some interesting additional information concerning transmission by double walls has been published in abstract form by P. E. Sabine.* The average reduction of intensity of sound, when transmitted by a single solid wall, was measured over the frequency range 128 to 4096. A second solid wall of the same

* P. E. Sabine, *Phys. Rev.*, **27**, 116, 1926.

weight and material was then built without any structural connection with the first and with an intervening air-space of 2 in. between the two walls. The effects of structurally bridging and of filling this space with different materials were determined by measuring the transmission of sound through the double wall thus formed. The reduction factors for various composite walls of this type are given in Table XVII. The conclusion is drawn that the bridging action of a filler of absorbent material more than offsets the reduction of acoustical energy due to absorption by such a material.

TABLE XVII.—SOUND TRANSMISSION THROUGH DOUBLE WALLS (P. E. SABINE)

Type of Wall.	Sound reduction factor (I_1/I_2).
Single wall	420
Double wall, bridged with wood	10,300
,, ,, sawdust-filled	8,700
,, ,, slag-filled	11,300
,, ,, felt-filled	31,000
,, ,, 2-in. air-space	32,000

Watson Method of Measuring Transmission

Reference has already been made (p. 104) to the method adopted by Watson for measuring the transmission and reflection of sound by panels built into an aperture in the wall between two adjacent rooms, and results giving the transmission of sound through various thicknesses of hair-felt were presented in Fig. 50.

In studying thin gypsum-plaster partitions on expanded metal lath (about $\frac{1}{2}$ in. thick), Watson noticed variations in transmission during the setting of the plaster. The effect of applying pressures to the centre of the panel until it broke was to alter the natural frequency of the partition for flexural vibrations, and maxima and minima of transmission were observed as the pressure was increased step by step. With thick partitions—2-in. solid plasterboard and plaster partition—the transmission began to increase when cracks developed, and continued to increase as the cracks became larger.

For thick partitions the results were generally in agreement with Sabine's in that the more massive structures transmitted least sound. Full details of Watson's investigations do not, however, appear to be available. His method differs from that of Sabine in that incidence at a definite obliquity is used. Also the experimental rooms may be much smaller than those required for the reverberation method. This latter is an advantage, since existing rooms of moderate size in basements of buildings may sometimes be adapted for the Watson method, whereas the Sabine method would probably necessitate the erection of a special building.

N.P.L. Measurements on Transmission

As already mentioned (p. 105) the Watson method is receiving attention at the National Physical Laboratory.* Fig. 75 illustrates the disposition of the apparatus. Partitions of the test material 5 ft. × 4 ft. in size are clamped over an aperture in the wall between two adjacent sound-proof rooms.

* Davis and Littler, *Phil. Mag.*, **3**, 177, 1927.

In one a source of sound, in conjunction with a paraboloidal mirror 5 ft. in diameter, directs a fairly uniform beam of sound towards the test partition.

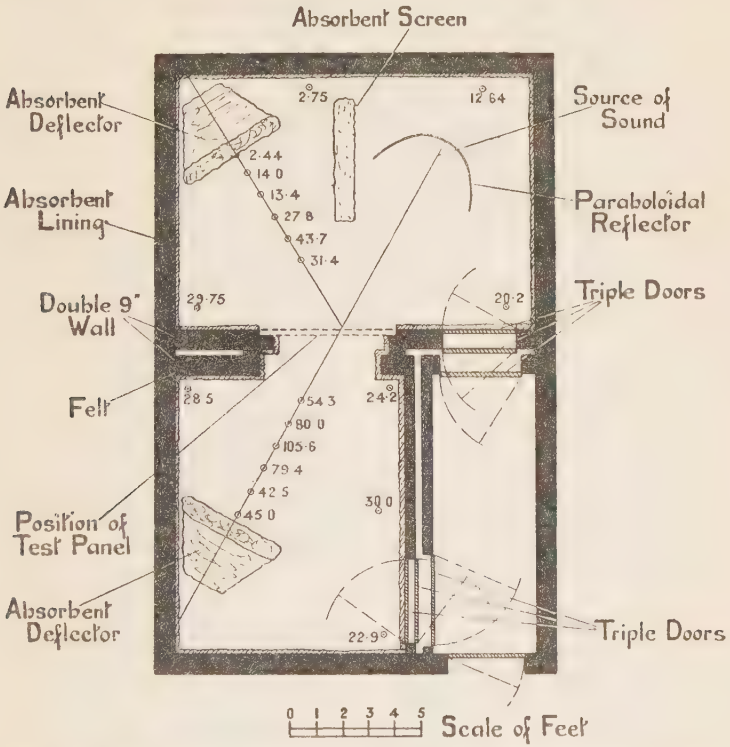


FIG. 75.—Sound-proof rooms at the N.P.L. The various numbers express the amplitudes of the acoustic disturbances at the points indicated, the test aperture being open.

Measurements of intensity are made on the axes of the transmitted and reflected beams respectively.

The sound-proof rooms, which are in a particularly silent situation in the basement, have walls about 2 ft. thick, concrete floors, and masonry ceilings. The wall between the two rooms is composed of two 9-in. brick walls, separated from each

other by a $4\frac{1}{2}$-in. air cavity and from the ceiling by a layer of felt. Apart from the test aperture, there is no direct communication between the rooms, and each is entered through three sound-proof doors from the annexe shown.

To reduce the intensity of sound in the region outside the main beams, and to minimise the occurrence of stationary waves, the walls, ceilings, and floors of the rooms have been thickly covered with absorbent materials. Special attention has been paid to the corners towards which the sound beams are directed, and absorbent deflectors inclined forward at 45 degrees have been placed in these situations. To prevent direct sound from the source from interfering with the reflected beam, an absorbent partition has been placed in the centre of the source room. Figs. 76 and 77, Plate XXI, are photographs of the source room and transmission room respectively taken in each case through the test aperture.

The source of sound used is an electrical loud-speaker operated by means of alternating current of approximately pure sine-wave form as generated by a valve oscillator. Telephonic apparatus is employed for measuring sound intensity. The complete electrical equipment is similar to that previously described for the production and measurement of pure tones (p. 25).

Measurements of intensity are normally made at every foot distance along the beams, reference points being provided by a series of light bobs suspended from the roof by silk threads. It was found that in the absence of a test partition the general intensity (in energy units) in positions in the reflection room, screened from direct radiation from the

FIG. 76.—View of N.P.L. source room through test aperture, showing parabolic reflector and heavily lagged walls. See p. 200.

FIG. 77.—View of N.P.L. transmission room through test aperture showing microphone in position. See p. 200.

[*To face page* 200.

loud-speaker, was only about 0·16 per cent. to 4 per cent. of the intensity in the transmitted beam. In the transmission room the intensity of stray sound outside the beam varied from 11 per cent. of the mean to 20 per cent. Some positions of reduced intensity (nodes) still occur in the length of the beam, the energy varying about ± 50 per cent. from the mean: in spite of this, however, transmission coefficients obtained for a given material are largely independent of the position in the beam at which the measurement was made. The incident beam is moderately uniform over a width of 2 ft. and over a width of 7 ft. it drops to about 25 per cent. of its maximum. The amplitudes of the acoustic disturbances in various parts of the two rooms are given by the numbers in Fig. 75, the test aperture being open.

In the test of a partition clamped over the aperture, a series of readings are taken in the transmitted and reflected beams at positions which are exactly the same as those adopted with the uncovered aperture.

Work with a frequency of about 2000 showed that for sound of short wave-length it is important that the test material (felt, etc.) should be so stretched over the aperture that its surface should exhibit no convexities or concavities: otherwise such irregularities exert focussing effects and so render the observations valueless. Reflection readings are more affected than transmission readings. For sounds of lower frequency, say below 1000, the effect is not very appreciable.

In order to determine the extent to which transmission and reflection ratios are dependent on the points at which measurements are taken, experiments were conducted as follows. With the aperture

uncovered the intensity of sound along the length of the transmitted beam is measured at intervals of 3 in. A material is then clamped over the aperture and the process repeated, readings of intensity being taken at the same positions as in the case of the uncovered aperture.

The results of such a series are given in Fig. 78, a

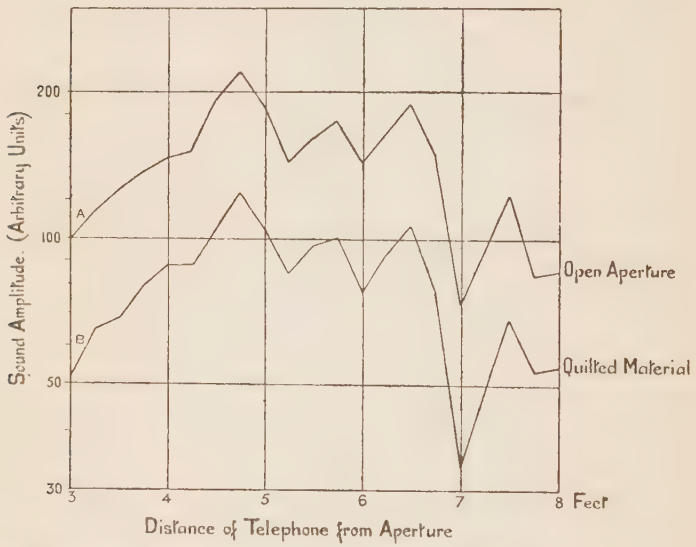


FIG. 78.—Exploration of sound beams transmitted through test aperture (A) when open and (B) when closed with a quilted material.

partition of quilted material being chosen for the investigation. The abscissæ represent distances along the beam and the ordinates the amplitudes in arbitrary units, plotted on a logarithmic scale. The two curves obtained are strikingly similar and are practically parallel. Since on a logarithmic scale equal distances between ordinates imply equal ratios, this parallelism of the two curves indicates that the effect of placing a partition over the aperture is to

reduce the intensity of the transmitted sound everywhere in the same ratio.

Similar results obtained in the case of the reflected beam show that the effect of covering a good reflector such as a mahogany board with, say, a layer of felt is to reduce the intensity of the reflected beam in nearly the same ratio at all points of the beam. For the partitions so far tested the values obtained for the transmission and reflection ratios are largely independent of the positions at which the measurements are taken.

The presence of the stationary wave systems in the chambers thus appears to have little effect upon the measured ratios. However, the systems could, if desired, be broken up and reduced either by arranging a moving source or by causing the source to emit a sound of oscillating pitch instead of a note of steady frequency.

For a frequency of 700 vibrations per second, the mean results for the transmission through a number of materials are given in Table XVIII, which also gives the results for the reflecting power of certain absorbent materials when backed by a stout (2-in.) mahogany board. For these absorbents the complementary fraction $(1—r)$ probably corresponds to some extent with the Sabine absorption coefficient of the surface of a room built of 2-in. mahogany panels, and lined with the material in question.

Results for the transmission through from 1 to 4 layers of hair-felt are given in Table XIX: a frequency range of from 250–1600 being covered. Figs. 79 and 80 show the results as a family of curves: in the first, the abscissæ express thickness of felt; in the second they express the frequency of

TABLE XVIII.—SOUND TRANSMISSION AND REFLECTION RATIOS FOR VARIOUS PARTITIONS (N.P.L.)

(Frequency of source, 700)

Partition.	Reflection ratio (r) (mahogany =1).	Transmission ratio (t) (open aperture =1).
None	0·015	1·00
Blanket	0·05	0·66
Quilted material	0·50	0·32
Cane fibre board	..	0·008
Felt	0·46	0·14
Felt+blanket	0·42	0·12
Mahogany, 2-in.	1·00	0·00029
Composite partitions—		
Mahogany, 2-in+blanket	0·66	..
,, ,, +quilted material, loosely fastened	0·34	..
,, ,, +cane fibre board	0·77	..
,, ,, +felt	0·50	..

TABLE XIX.—SOUND TRANSMISSION THROUGH HAIR-FELT (N.P.L.)

(Thickness, 0·58 in. per layer ; Density, 12 lbs. per cubic foot)

Frequency of test sound.	Percentage energy transmitted by the following number of layers :—			
	1.	2.	3.	4.
250	24	11	5·3	3·6
400	23	9·5	4·2	2·1
500	25	8·9	4·1	1·4
700	22	7·4	2·2	0·9
1000	23	6·8	1·9	0·5
1600	26	6·0	1·0	0·2

the test-note. Logarithmic paper is used and, as will be seen, an approximately linear relation is then obtained between thickness and transmission.

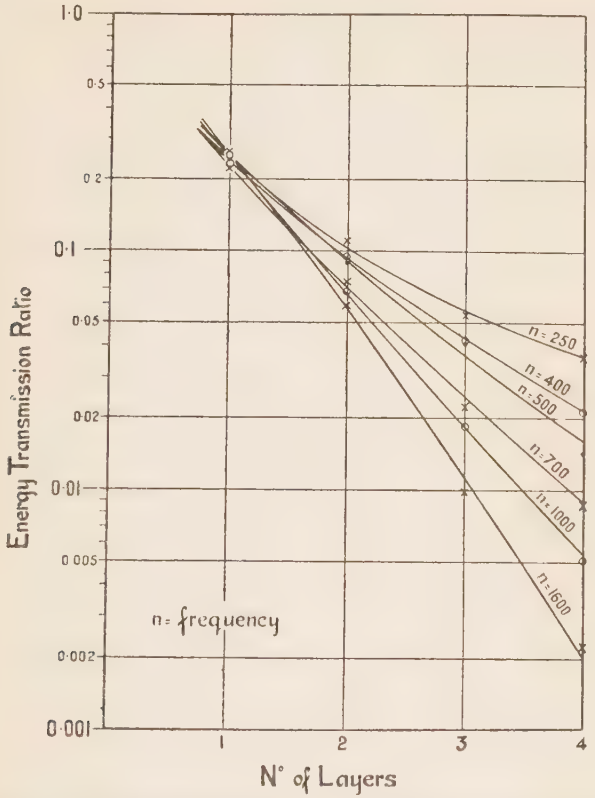


Fig. 79.—Sound transmission through layers of hair-felt at various frequencies (N.P.L.).

When the results in Fig. 79 are compared with Sabine's results for transmission through layers of felt (Fig. 72), it is seen that the graphs are generally similar and increase in steepness with increase of note frequency. The chief difference is that, while Sabine's curves are all straight lines, they do not

pass through the value unity when produced to zero thickness of felt; and, while the curves of Fig. 79

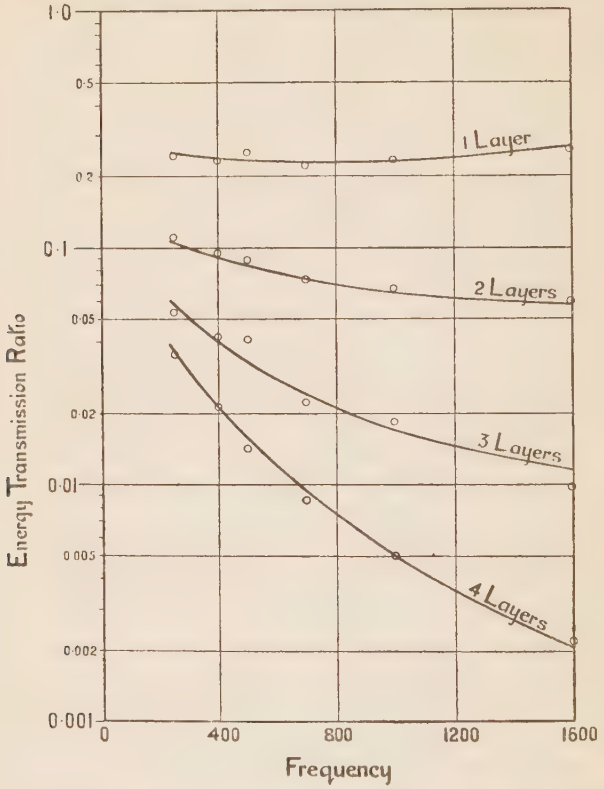


Fig. 80.—Sound transmission through layers of hair-felt at various frequencies.

would pass through the value unity, they are not quite straight.

Bureau of Standards Measurements on Transmission

Work on sound transmission by building materials has been in progress at the Bureau of Standards,

Washington,* for some time. Fig. 81 is a vertical section of the building erected for the purpose. As will be seen, the source room works in conjunction with one or other of two transmission rooms, according as the test material is mounted in an aperture in the ceiling or in the wall of the source room.

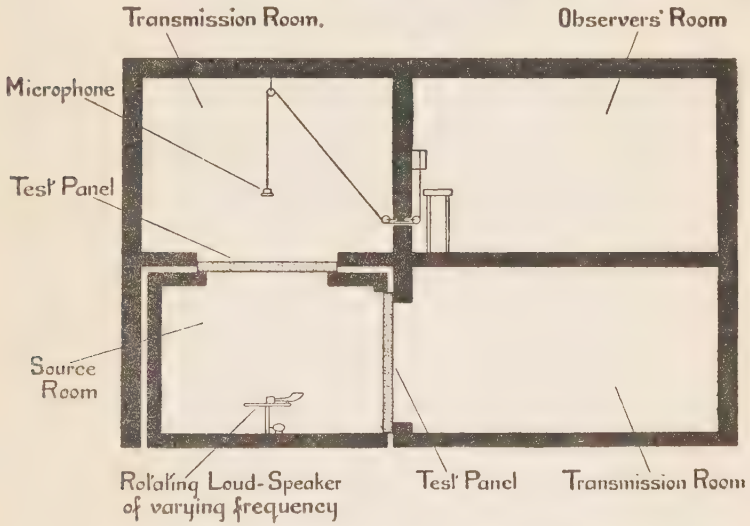


Fig. 81.—Bureau of Standards sound-transmission chambers.

The dividing walls consist of two 6-in. walls separated by a 3-in. air-gap. Provision is thus made for measuring transmission either through vertical partitions having dimensions 7 ft. × 6 ft. or through floor and ceiling structures of the same size.

Electrical loud-speaker and microphone apparatus is used in the measurements, the circuits being generally of the type indicated on p. 24. To break up interference systems in the acoustic fields and stir

* Eckhardt and Chrisler, *Sci. Paper, Bur. Standards*, No. 526, 1926.

up the sound in the various rooms, the position of the loud-speaker is varied by mounting it at the end of a rotating arm. Further, instead of using a note of a single frequency, the pitch is varied cyclically over a frequency band of the acoustic range 250 to 3470. The microphones employed for measuring the sound intensities are associated with a long-period galvanometer, so that the deflections give a time-average of the intensity. Measurements are not made near the source or near the test-panel, for the conditions there are found to differ somewhat from the uniform intensity distribution it is desired to attain. Despite the above precautions, however, an absolutely uniform distribution of sound is not obtained, even at appreciable distances from the source and panel, and, in practice, average values of the intensities at a number of points are taken. It occasionally happens, especially with high frequencies, that the interference pattern in the source room is such that the intensity actually rises as the receiver is moved away from the source, but it is found that the mean value of such a curve agrees closely with the mean value when the curve happens to slope the other way.

The general experimental procedure may be summarised as follows. With the test aperture open, *i.e.* with the panel absent, a series of measurements is made with the microphone at different places along a central line perpendicular to the face of the aperture. In general, the intensities at these points fall off as the distance of the receiver from the source of sound is increased. Suppose the mean values in the source room and transmission room are S and T respectively. The test-panel is now put in place and

the measurements repeated. The value of S is usually increased, say, to $(S+s)$, and that of T decreased, say, to $(T-t)$. Thus inserting the panel reduces the intensity in the transmission room in the ratio $\frac{T-t}{T}$, and increases the intensity in the source room in the ratio $\frac{S+s}{S}$. Had this greater intensity existed in the source room with the aperture open, the mean intensity in the transmission room would have been $T \cdot \frac{S+s}{S}$; and, as this is actually reduced to $(T-t)$, the true reduction factor of the panel may be taken as $\frac{T-t}{T} \cdot \frac{S}{S+s}$.

The panels tested consisted of different kinds of plaster used in building construction, mounted on a framework 7 ft. $\times$ 6 ft. $\times$ 4 in. thick. A wood-stud and lath (wood or expanded metal) foundation for the plaster was erected within each framework. Some of the partitions tested consisted of two plaster coats, $\frac{7}{8}$-in. thick, one on each side of the framework and thus separated from each other by a 4-in. air gap bridged only by the wooden studs. Solid plaster partitions were also tested in thicknesses up to 4 in. The reduction factor for the different partitions varied from about 10,000 for a gypsum-plaster partition on metal lath to about 10,000,000 in the case of a plaster partition on wood lath. In all cases the sound transmitted through the panels was less than $\frac{1}{10000}$ of the incident sound.

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